US006136246A

United States Patent [19]

Rauwendaal et al.

[11] **Patent Number: 6,136,246**

[45] **Date of Patent: *Oct. 24, 2000**

[54] **SCREW EXTRUDER WITH IMPROVED DISPERSIVE MIXING ELEMENTS**

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[73] Assignee: **Rauwendaal Extrusion Engineering**, Los Altos Hills, Calif.

[*] Notice: This patent is subject to a terminal disclaimer.

[21] Appl. No.: **09/241,822**

[22] Filed: **Feb. 1, 1999**

Related U.S. Application Data

[63] Continuation-in-part of application No. 08/966,272, Nov. 7, 1997, Pat. No. 5,932,159.

[51] **Int. Cl.**[7] **B29C 47/60**; B29C 47/62; B29C 47/66

[52] **U.S. Cl.** **264/211.21**; 264/211.23; 264/349; 366/79; 366/81; 366/84; 366/85; 366/89; 366/300; 366/301; 366/318; 366/319; 366/322; 366/323; 366/324; 425/200; 425/204; 425/208; 425/209

[58] **Field of Search** 264/211.21, 211.23, 264/349; 425/200, 204, 208, 209; 366/79, 81, 84, 85, 89, 300, 301, 318, 319, 322, 323, 324

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Primary Examiner—Leo B. Tentoni

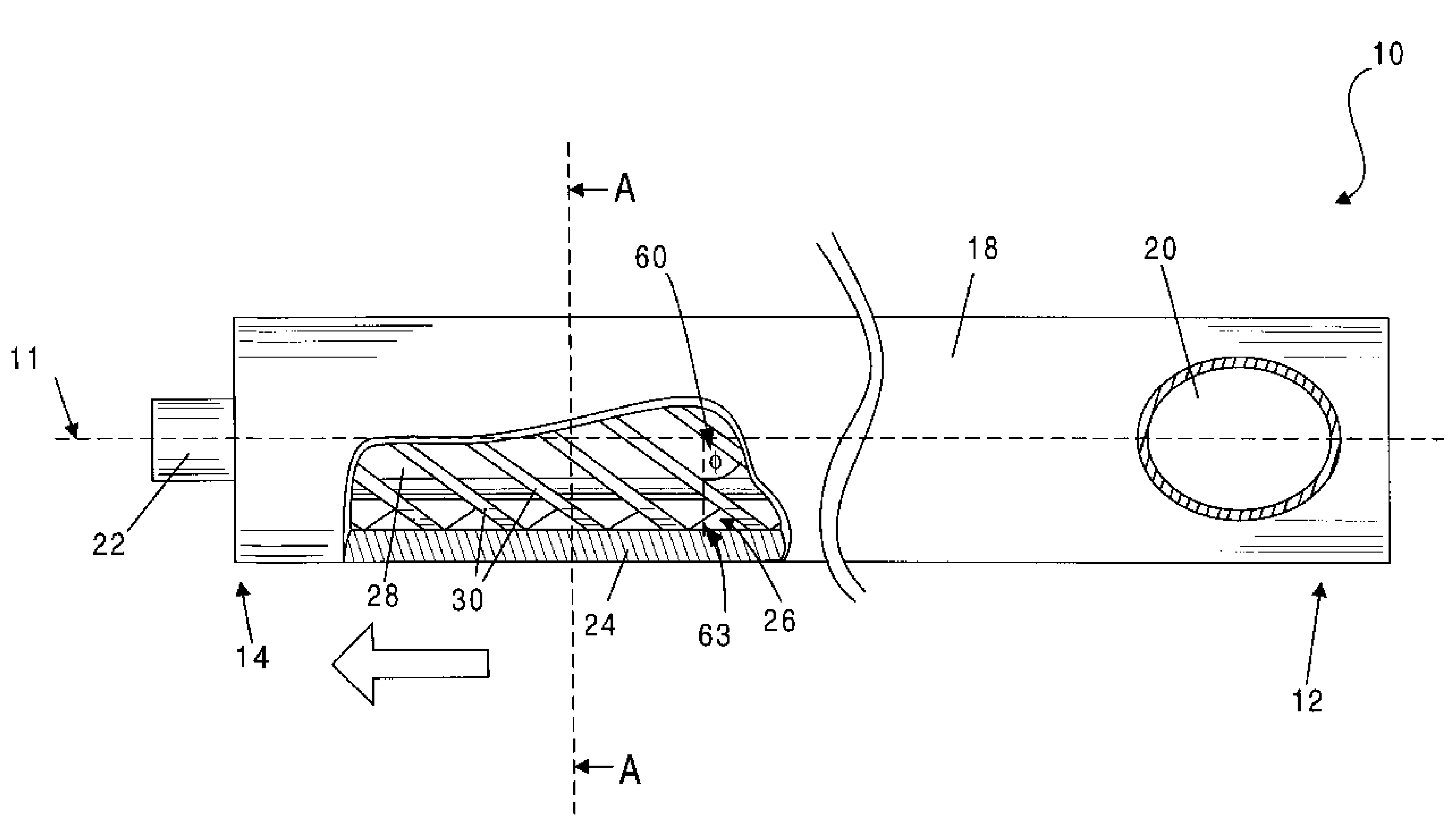
Attorney, Agent, or Firm—Larry B. Guernsey; Hickman Stephens Coleman & Hughes, LLP

[57] **ABSTRACT**

A screw extruder **(10)** having a barrel **(18)** which has a bore **(26)** defining an inner surface **(44)** and one or more extruder screws **(28)**, positioned within the bore **(26)**. The extruder screw or screws **(28)** include a central shaft **(34)** and one or more screw flights **(30)**. The extruder screw or screws **(28)** farther including one or more dispersive mixing elements **(204)**, **(234)**, **(308)**, **(406)**, **(508)**, **(558)**, which interact with the inner surface of the barrel **(44)** to form one or more progressively narrowing passages **(46)** through which material is forced into multiple regions of high elongational and shear stress **(480, (120)**, **(214)**, **(310)**, **(410)**, **(510)**, **(564)**.

A second preferred embodiment is a screw extruder **(10)** having a barrel **(18)** having a bore **(26)** defining an inner surface **(44)** and one or more extruder screws **(600)**, **(701)**, positioned within the bore **(26)**. The extruder screw or screws **(600)**, **(701)** include a central shaft **(602)**, **(706)** and a number of dispersive mixing elements **(604)**, **(608)**, **(714)**, which are configured and positioned to form a number of progressively narrowing passages **(606)**, **(716)** through which material is forced into multiple regions of high elongational and shear stress **(608)**, **(718)**.

36 Claims, 27 Drawing Sheets



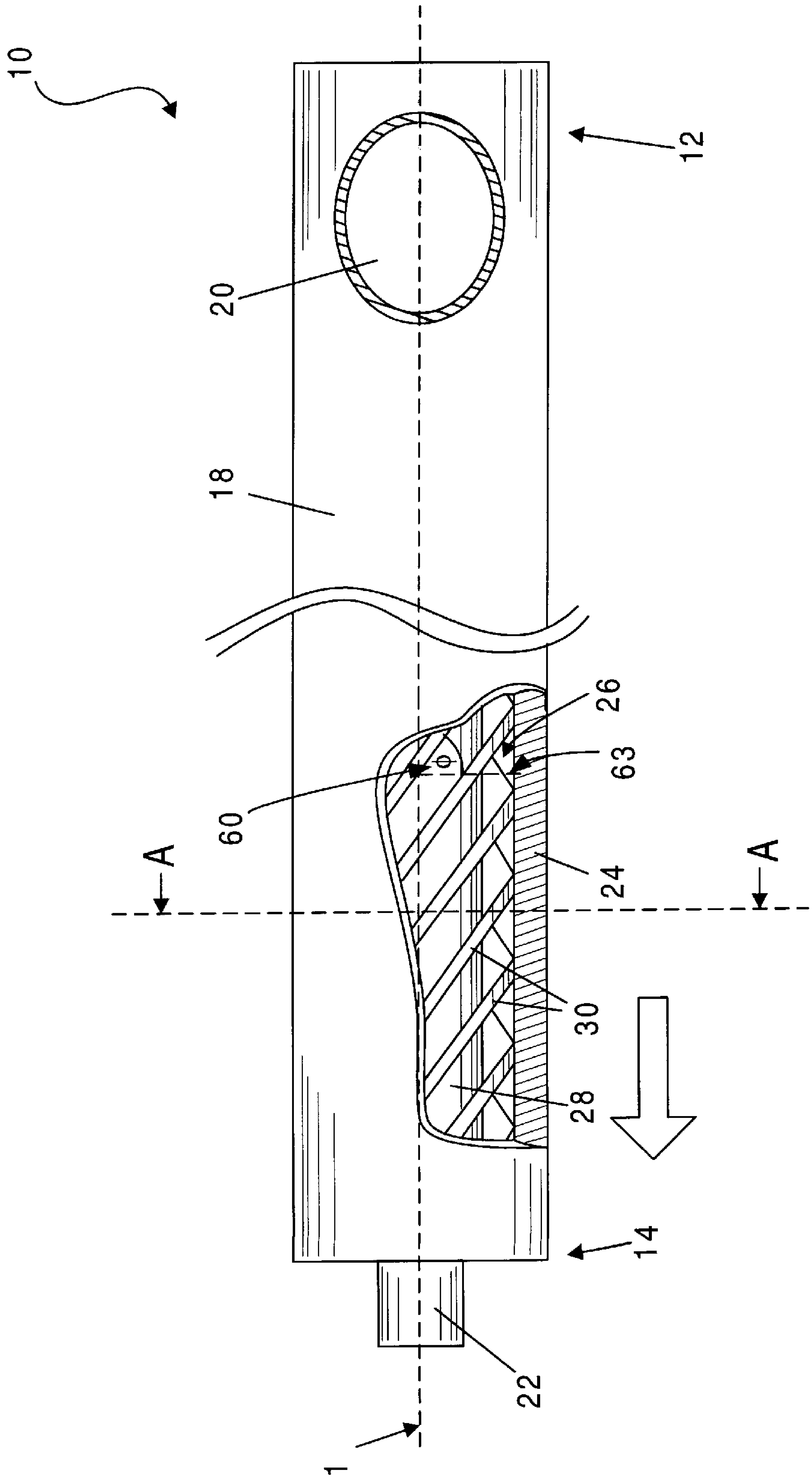


FIGURE 1

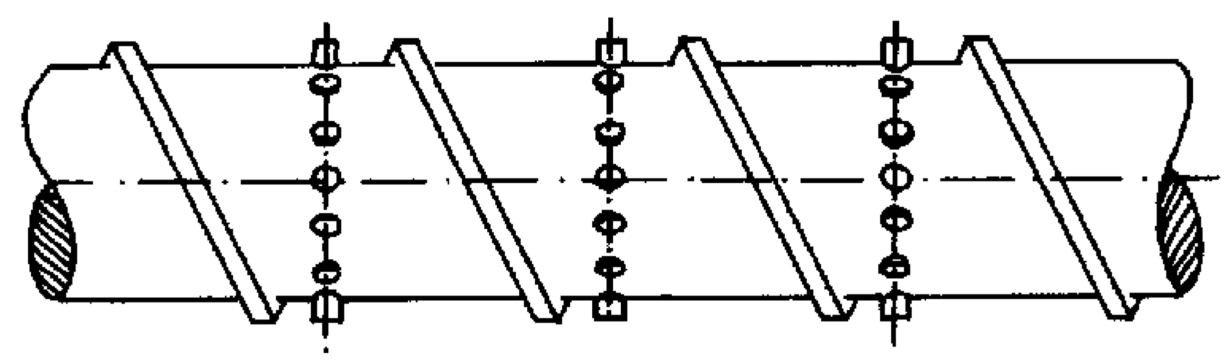


FIG. 2A

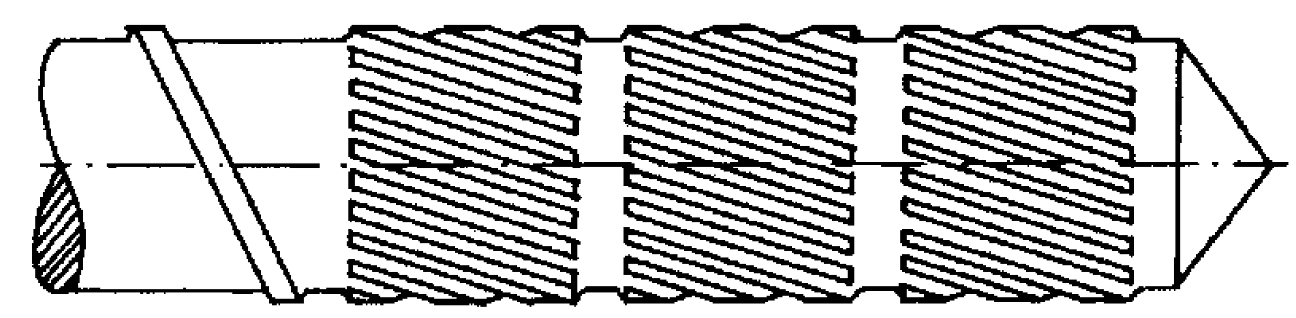


FIG. 2B

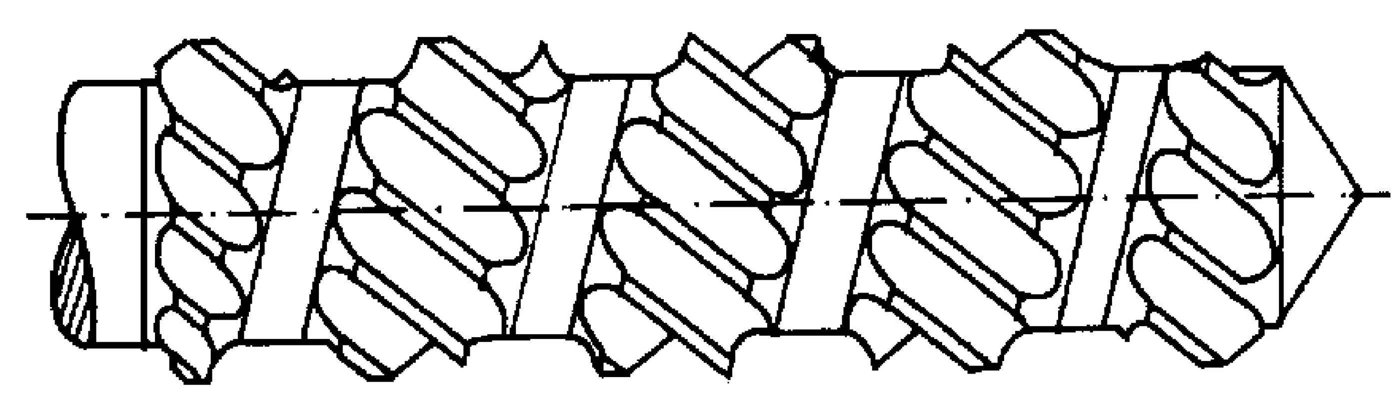


FIG. 2C

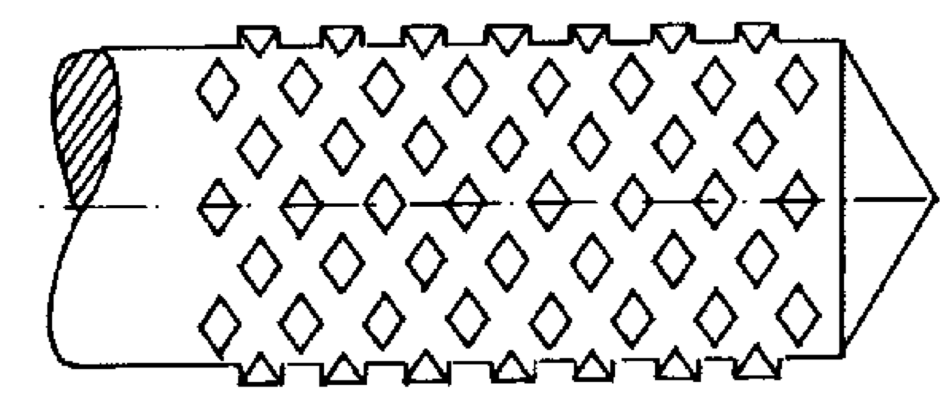


FIG. 2D

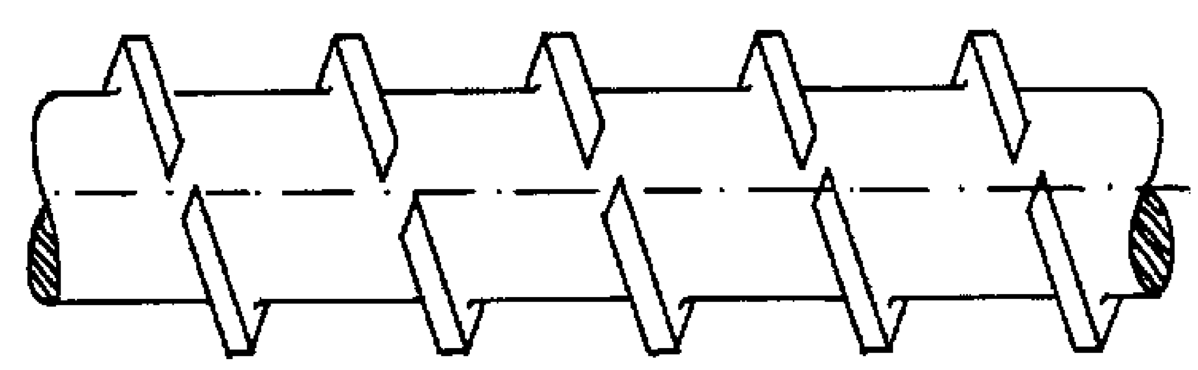


FIG. 2E

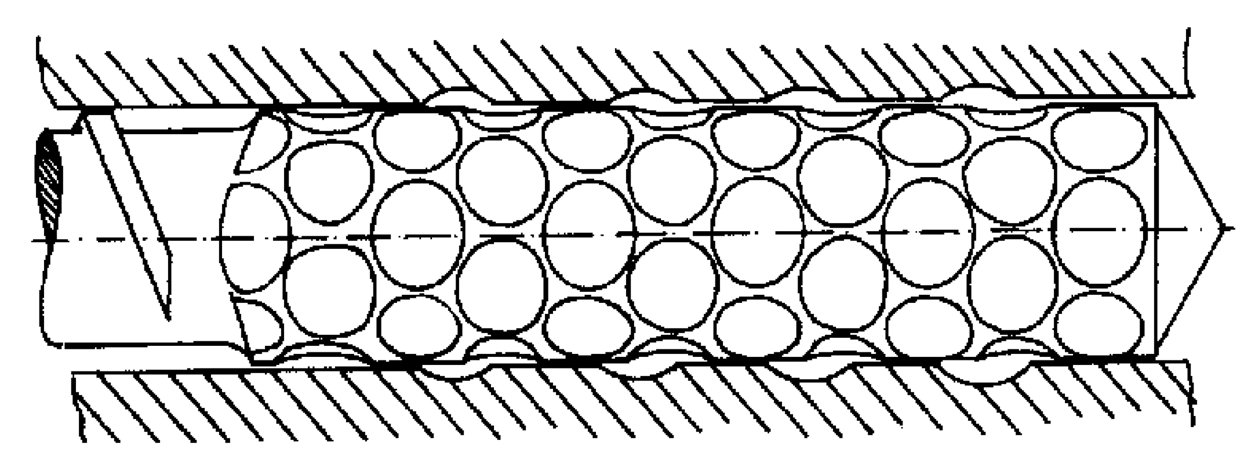


FIG. 2F

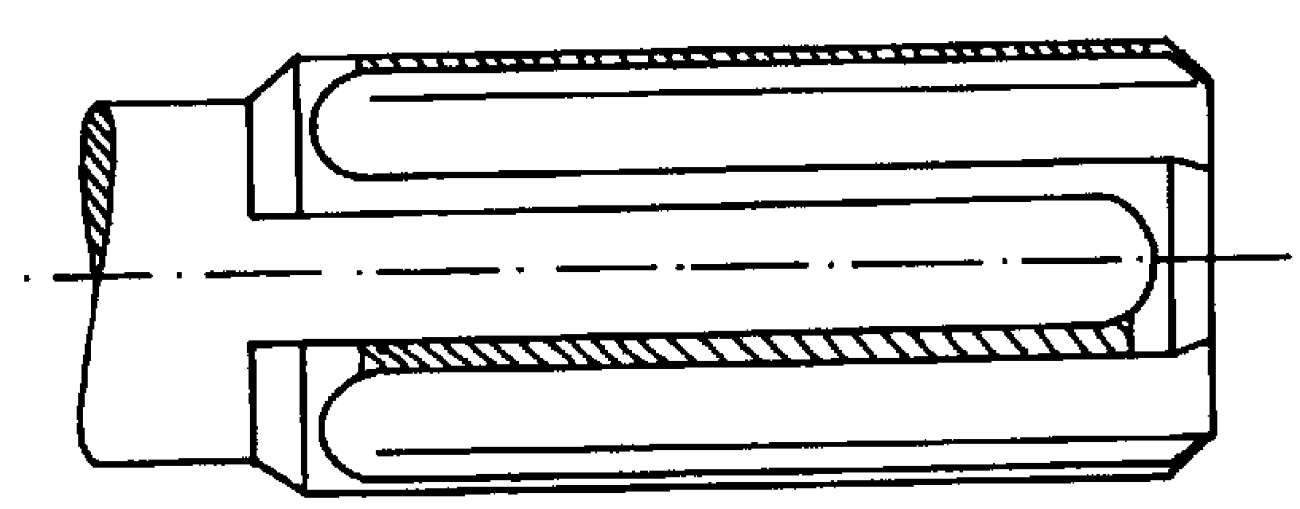


FIG. 2G

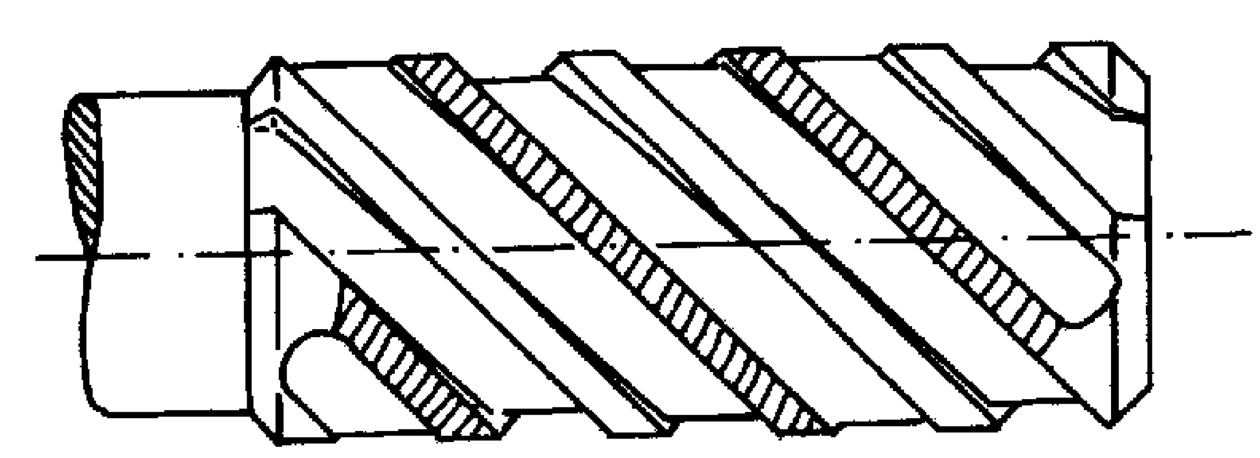


FIG. 2H

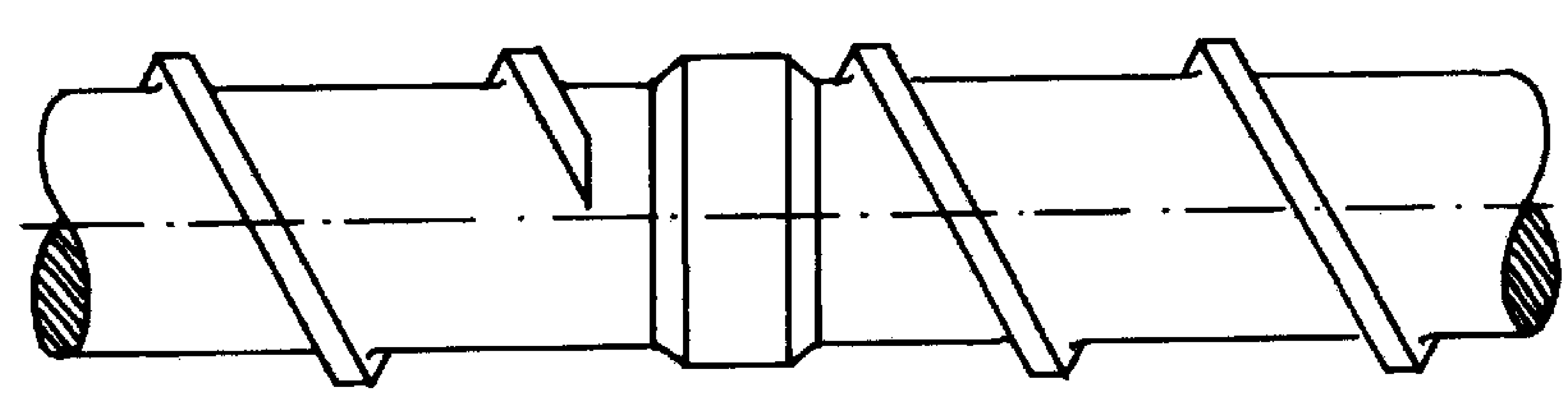


FIG. 2J

Prior Art

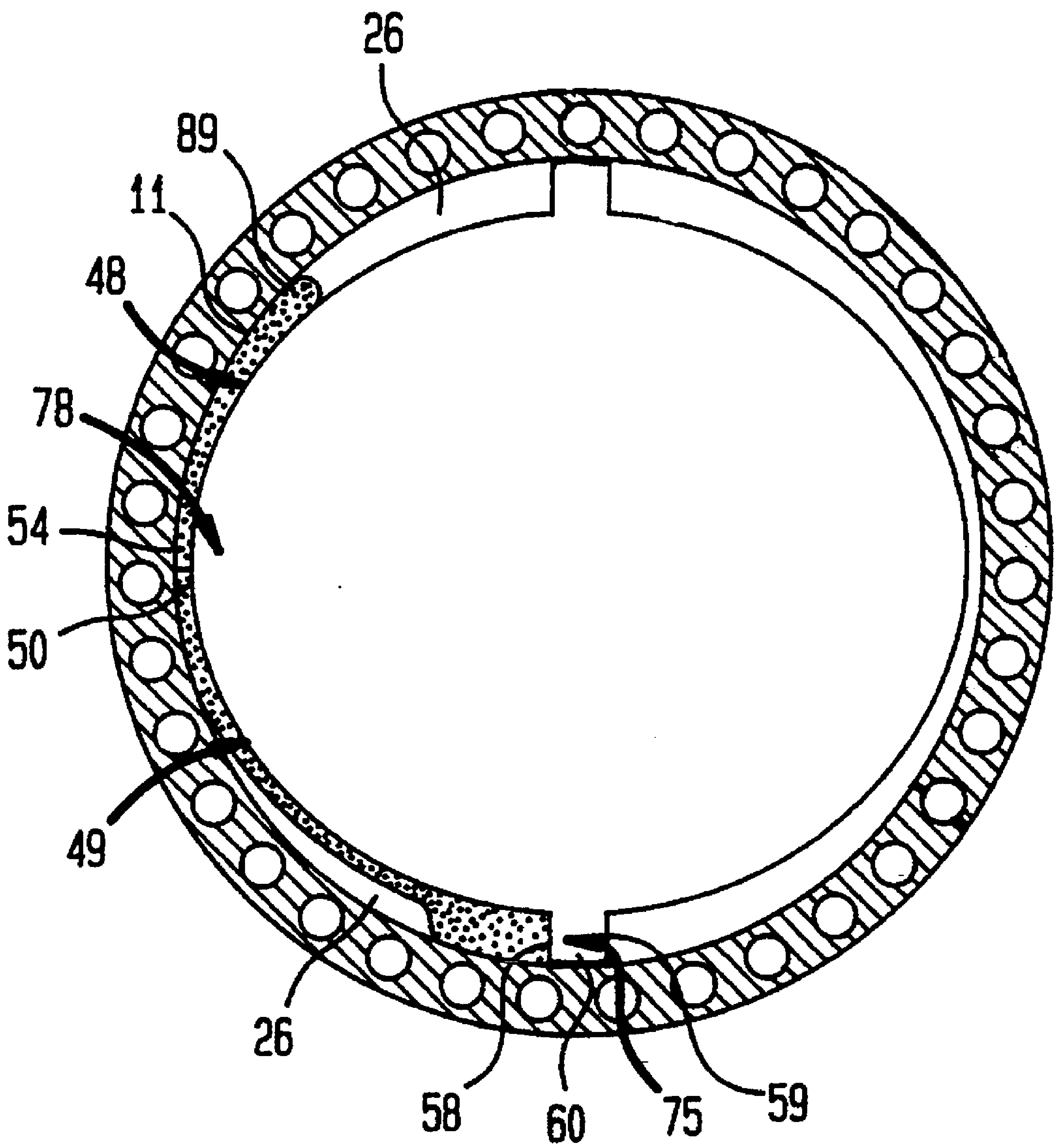


FIGURE 2K Prior Art

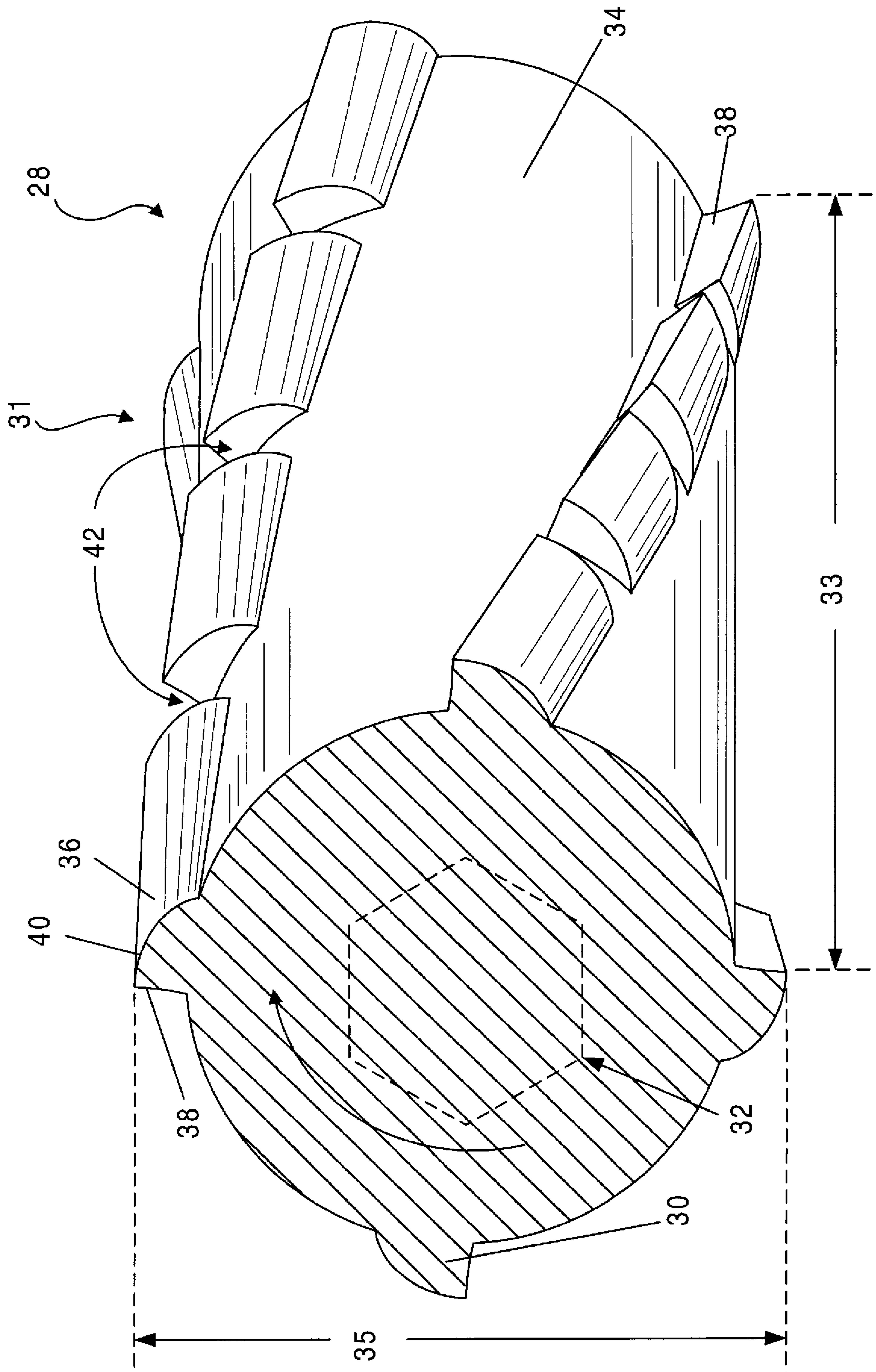


FIGURE 3

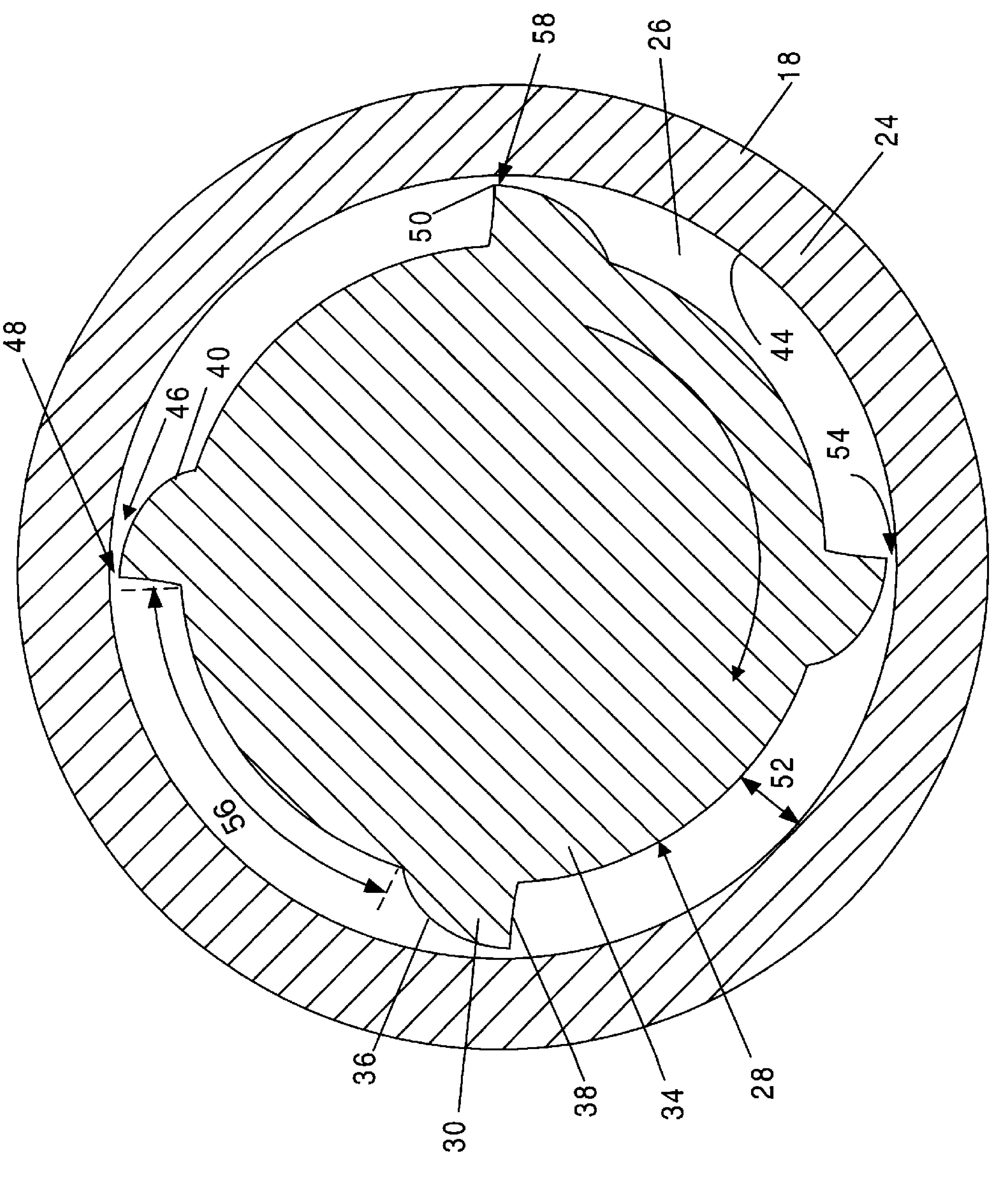


FIGURE 4

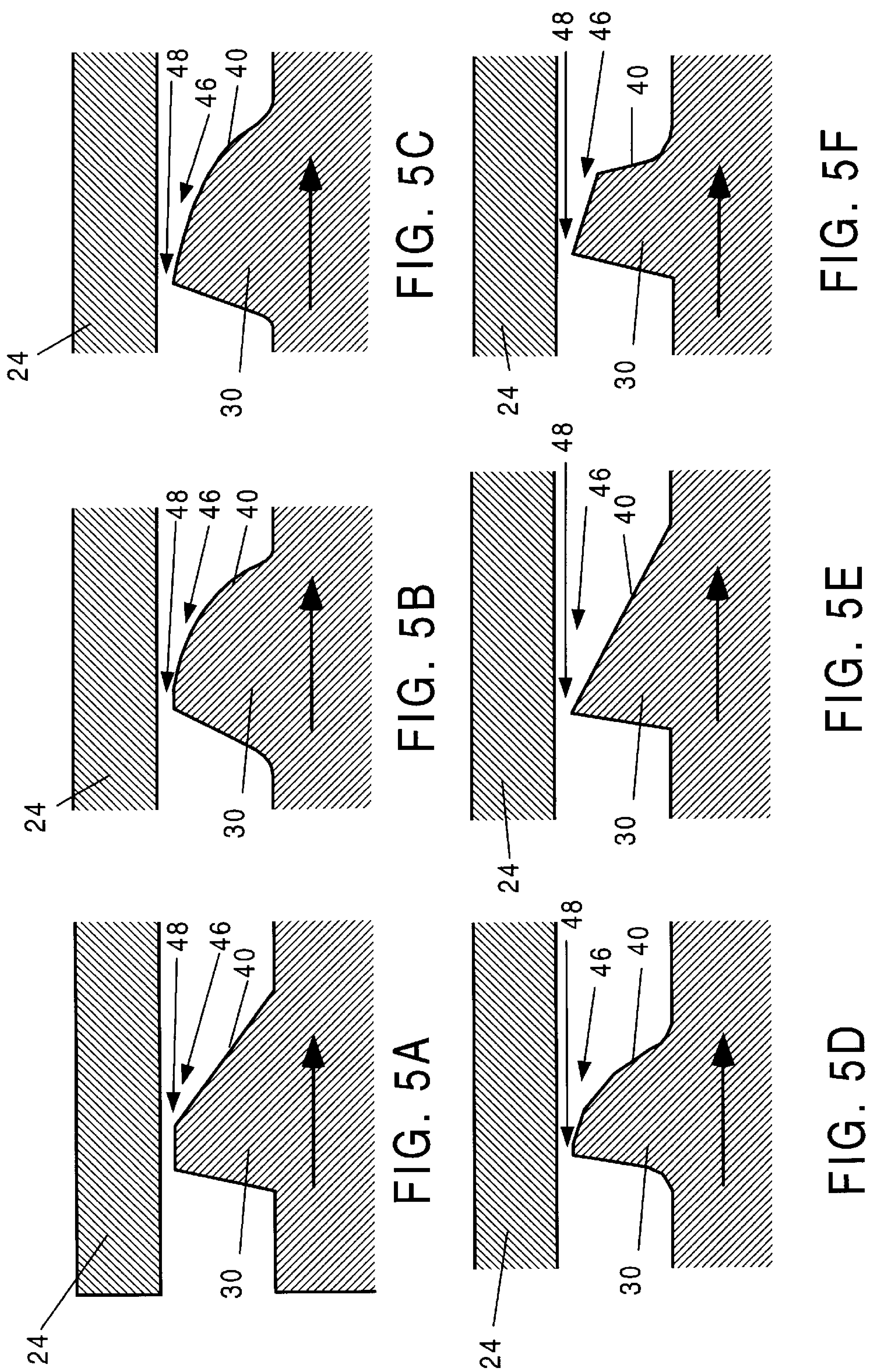


FIG. 5A

FIG. 5B

FIG. 5C

FIG. 5D

FIG. 5E

FIG. 5F

FIGURE 5 A-F

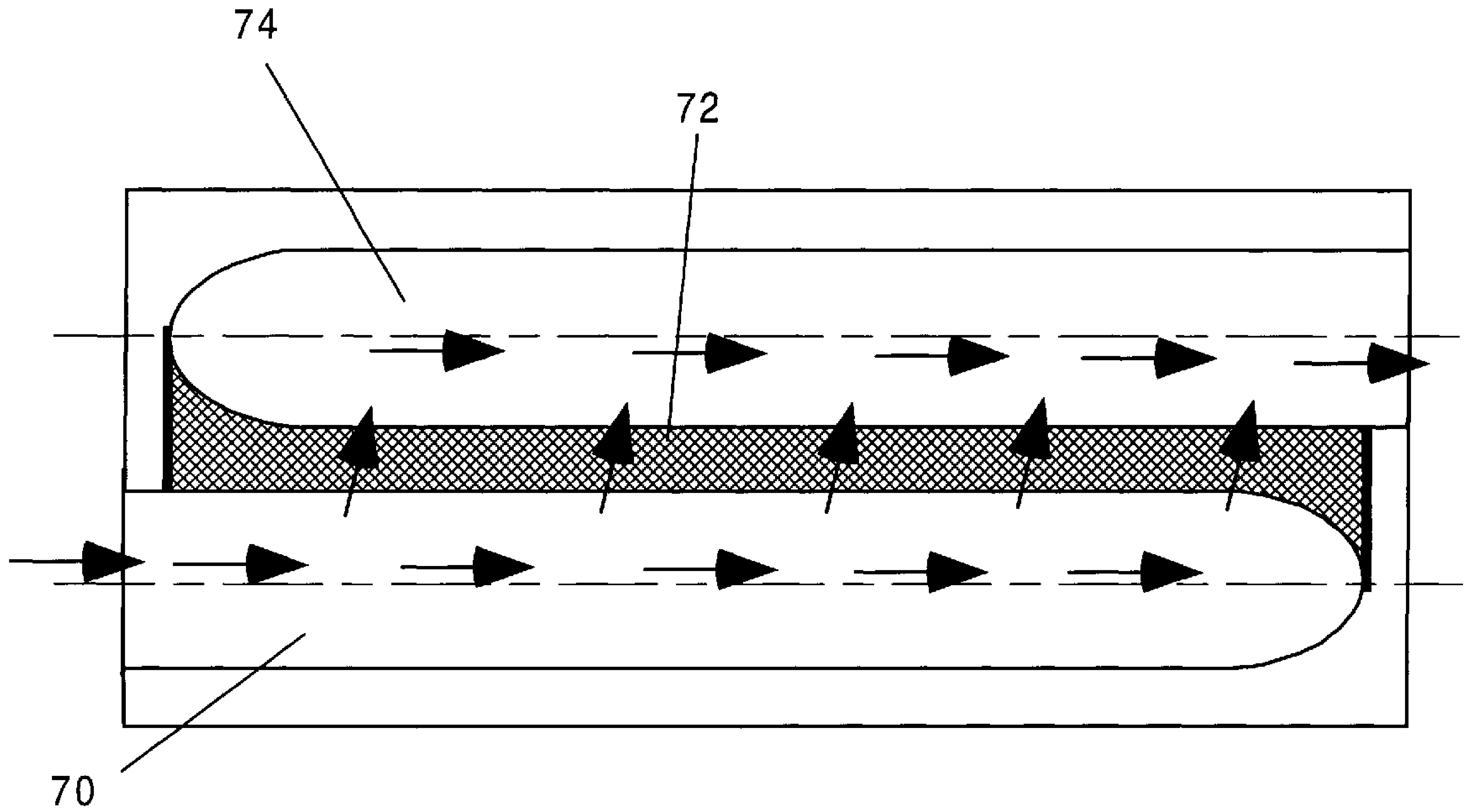


FIGURE 6 Prior Art

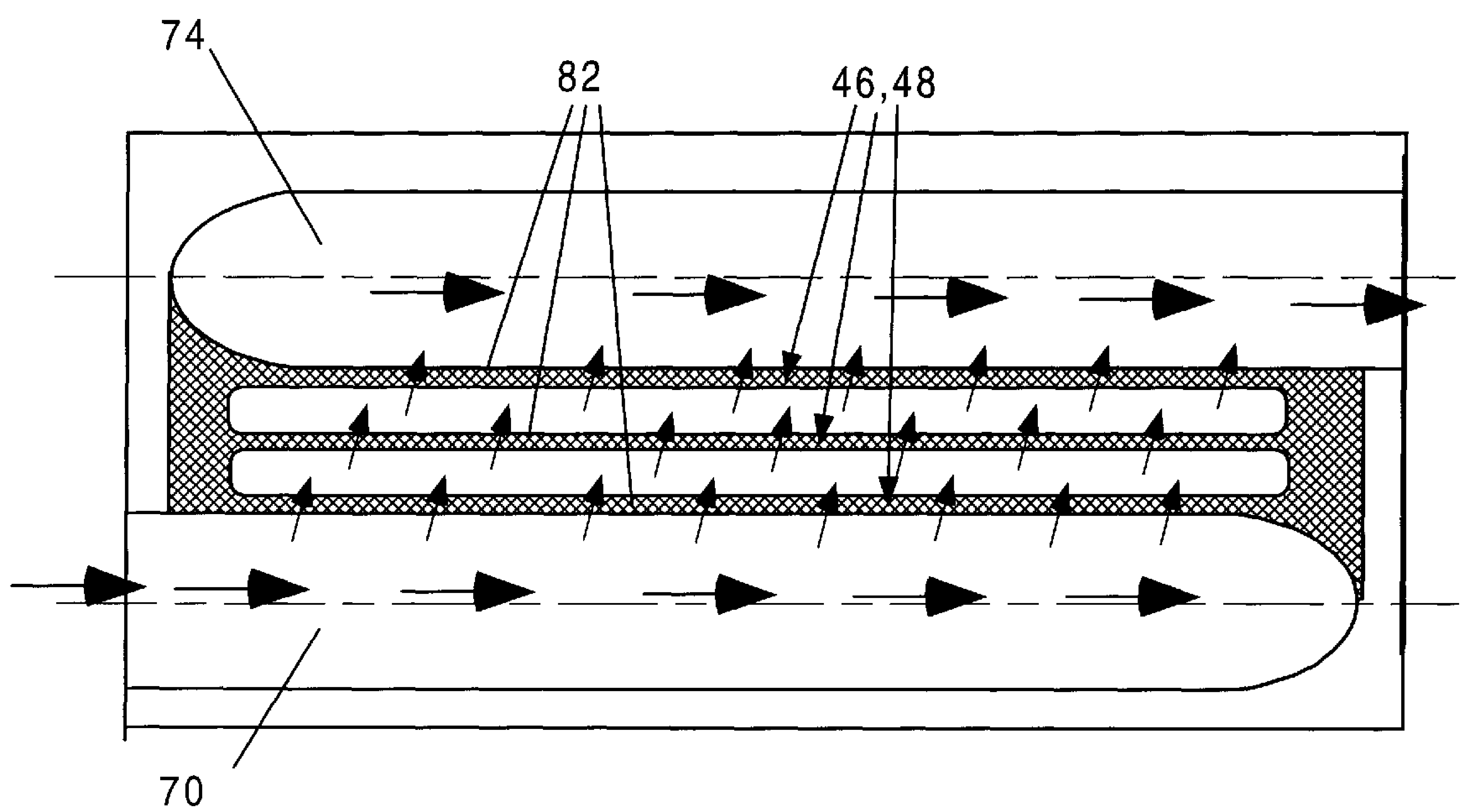
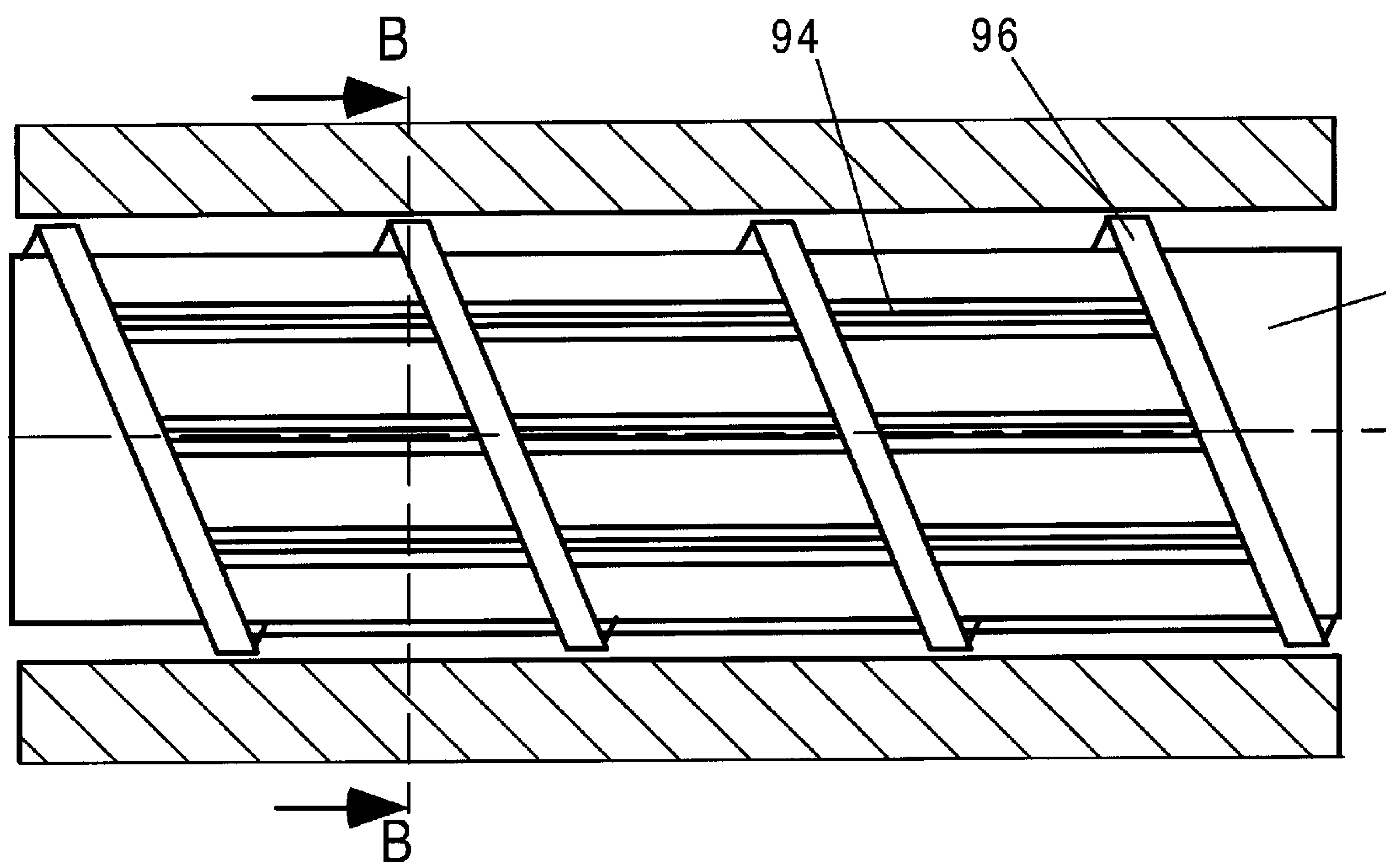


FIGURE 7



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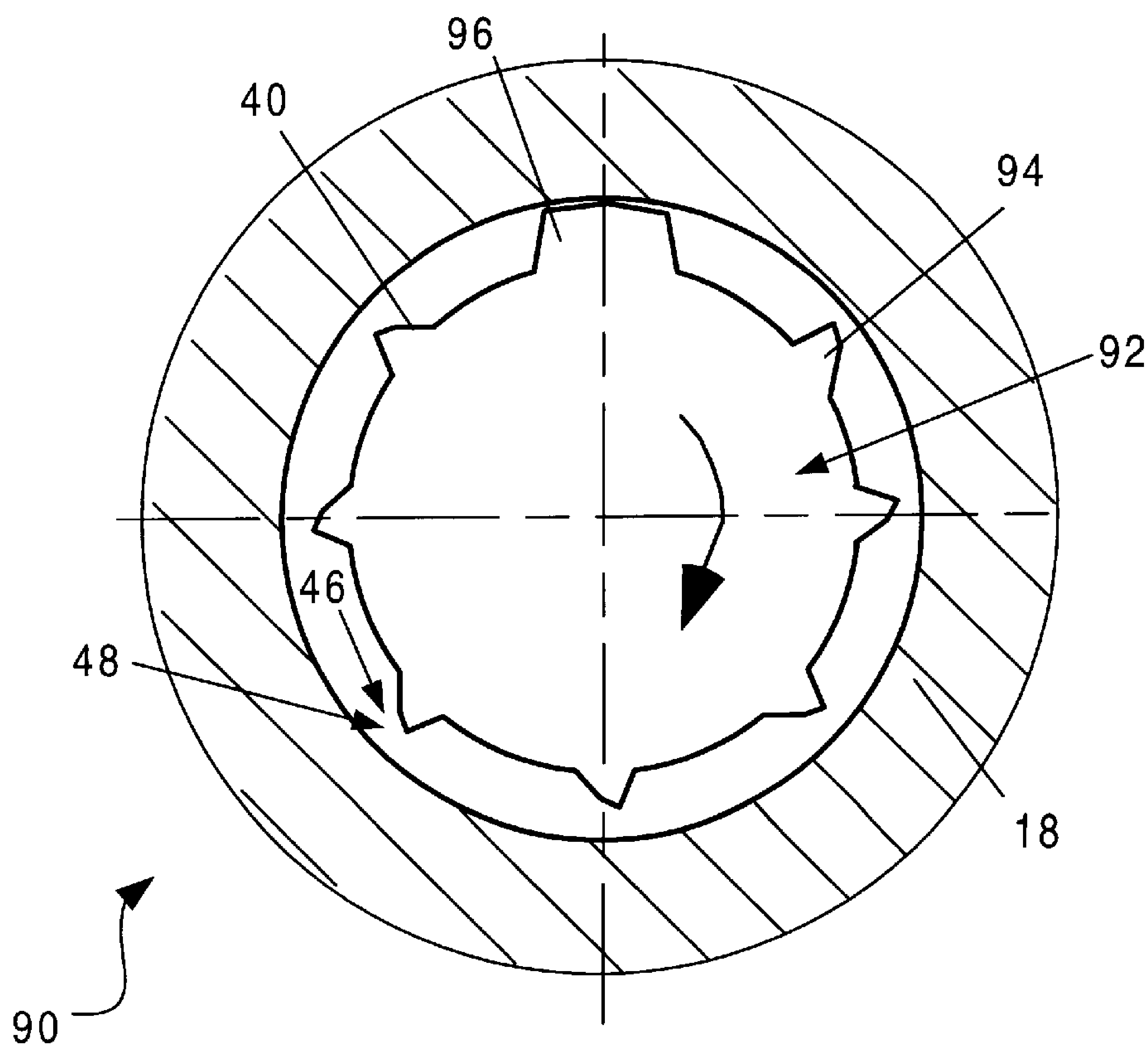


FIGURE 9

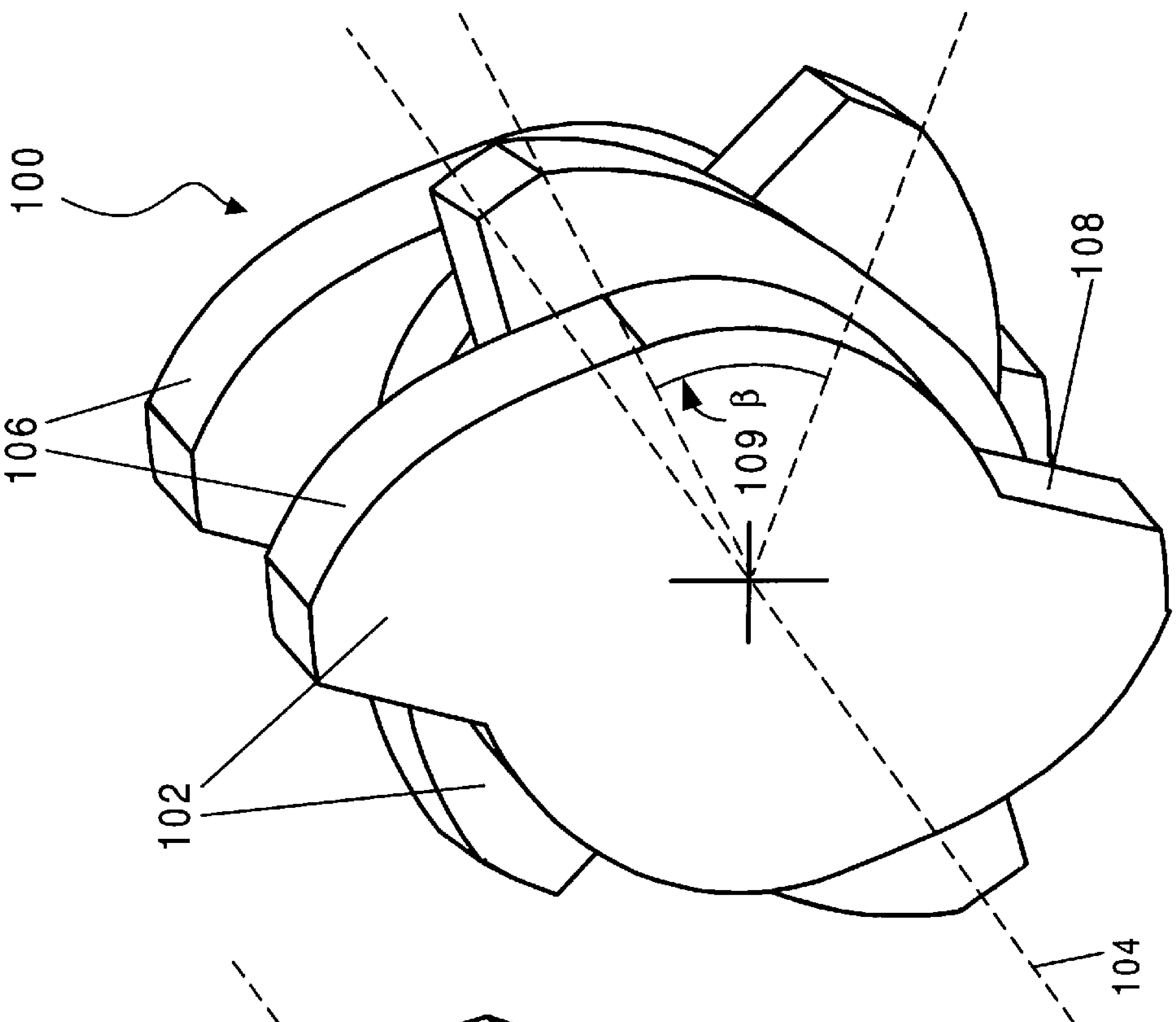


FIGURE 11

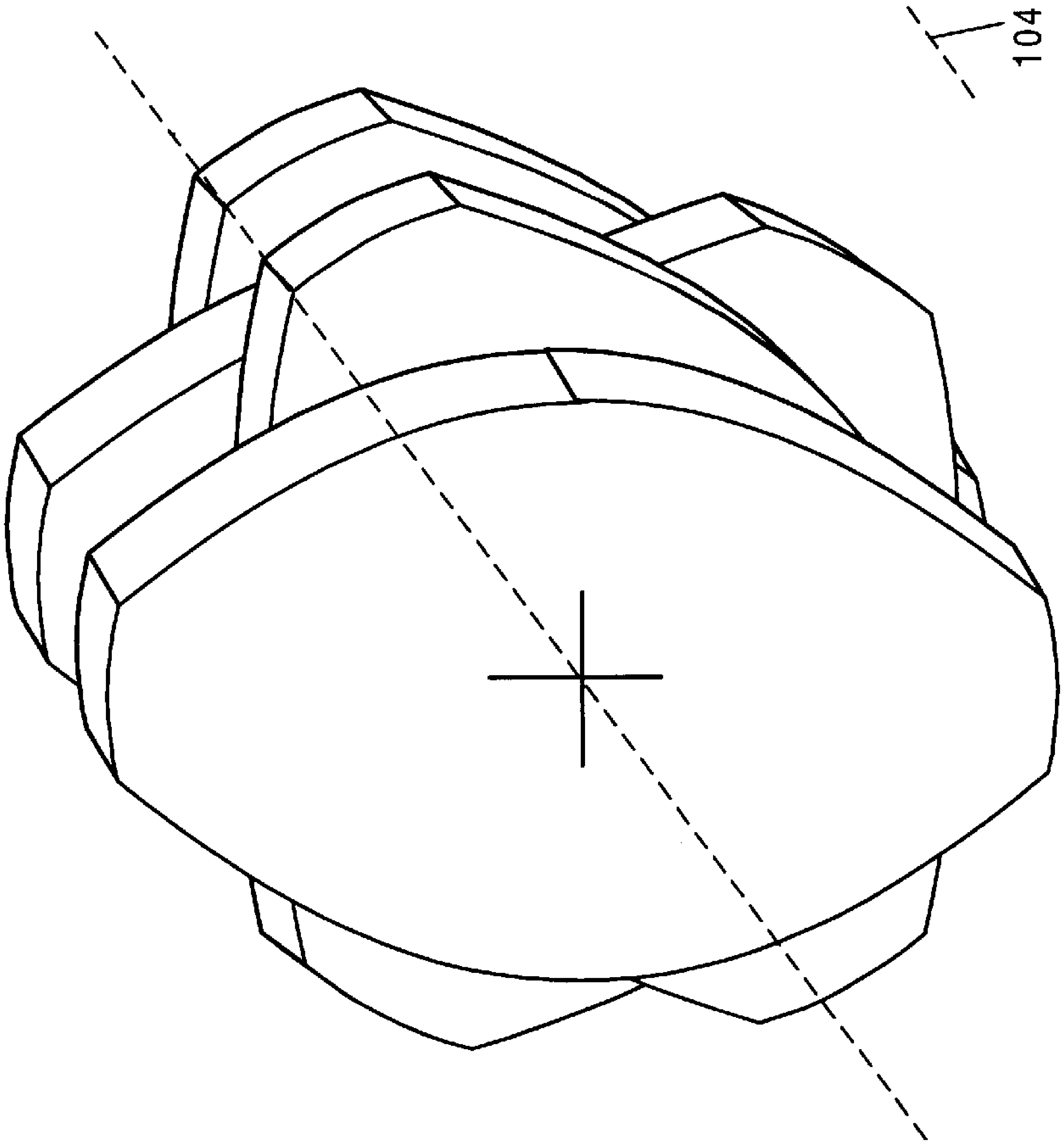


FIGURE 10 Prior Art

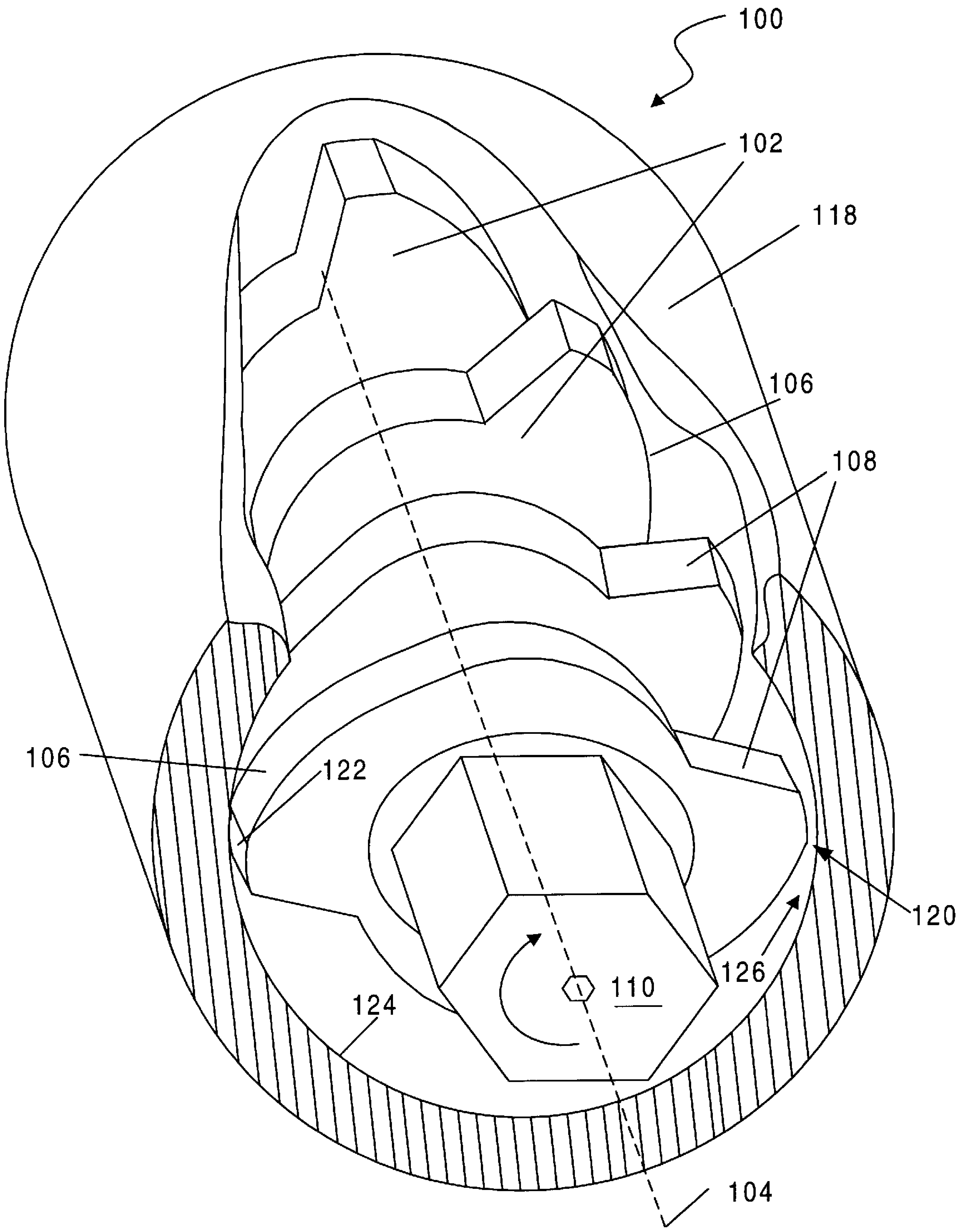


FIGURE 12

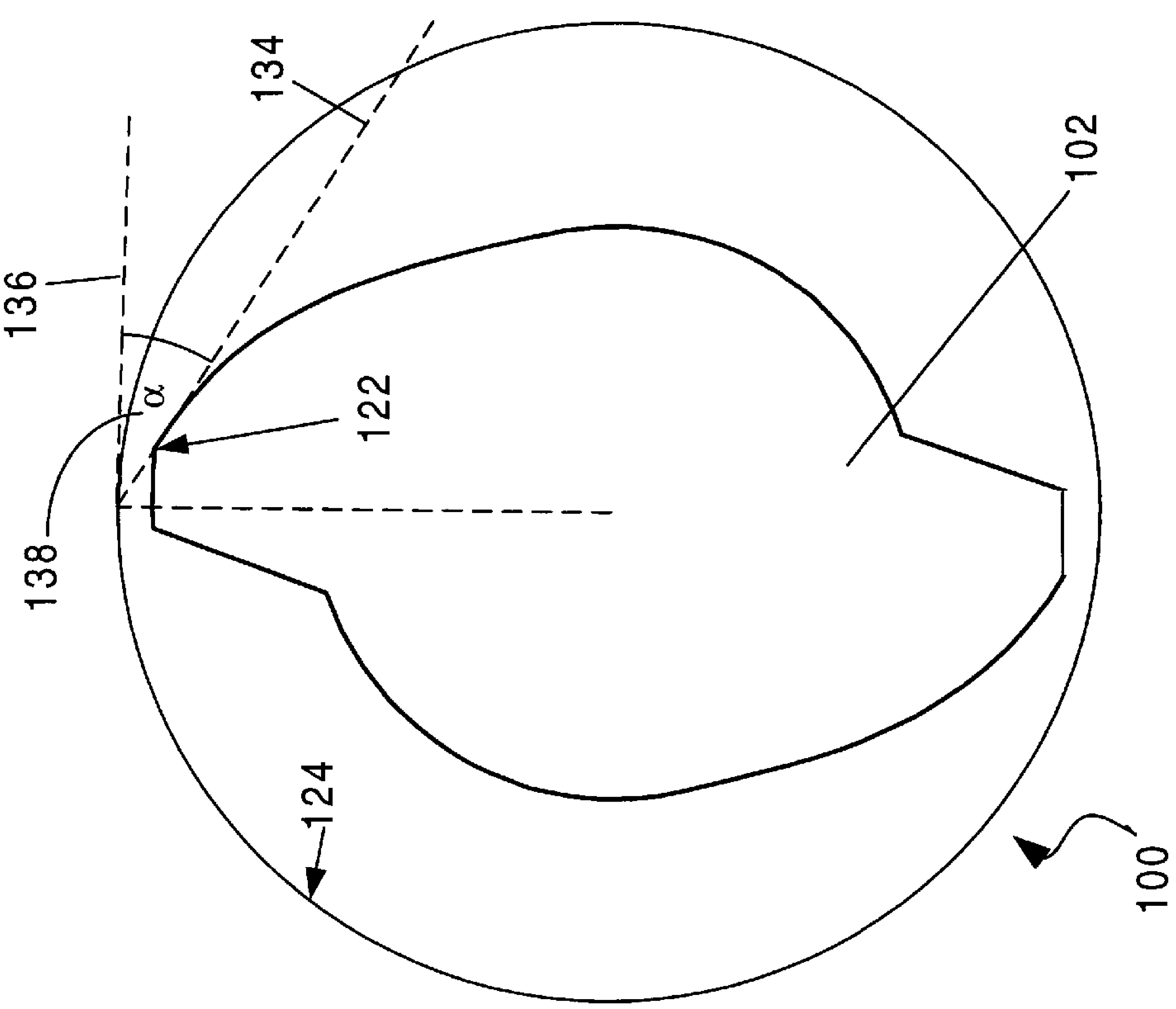


FIGURE 14

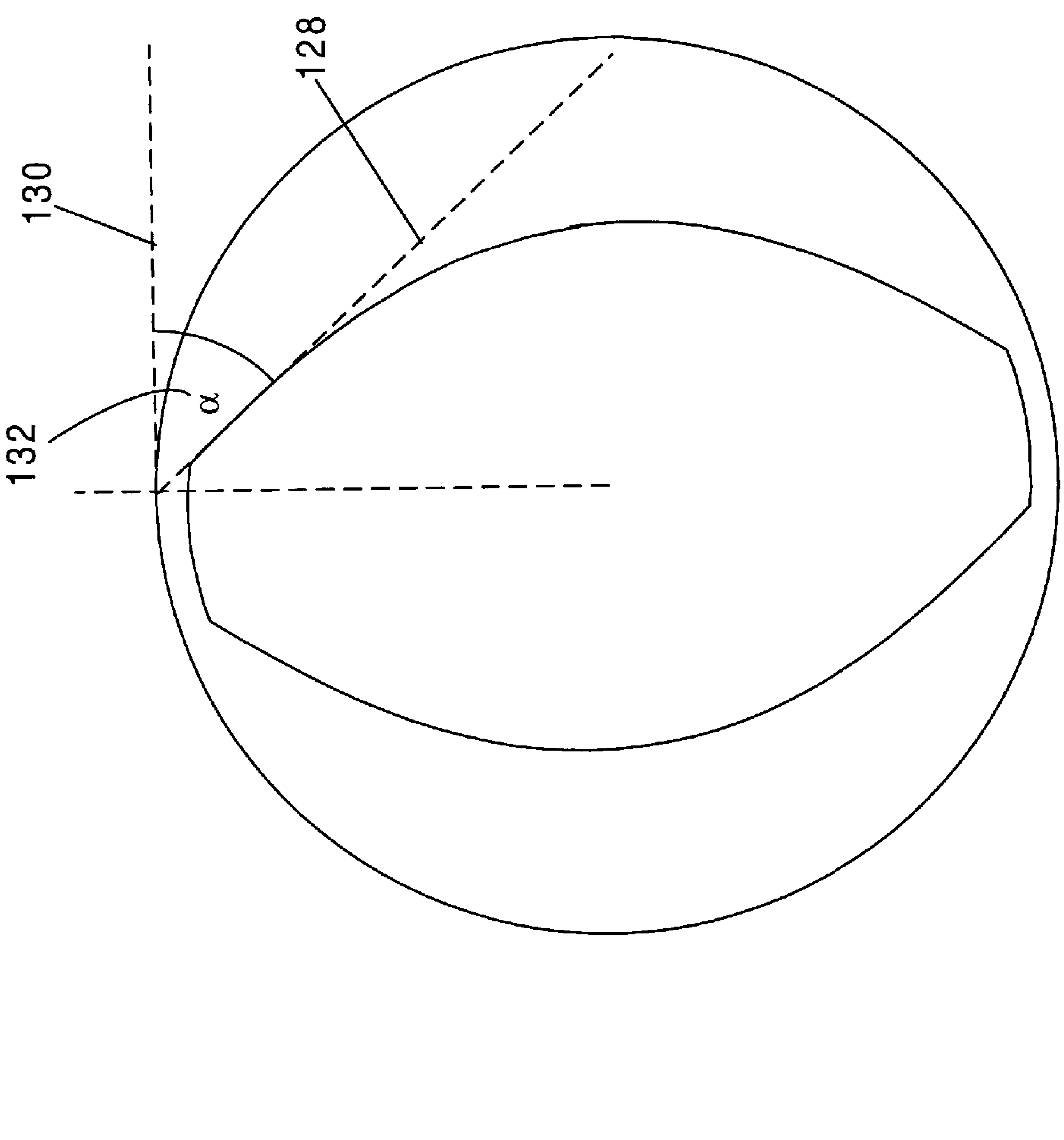


FIGURE 13 Prior Art

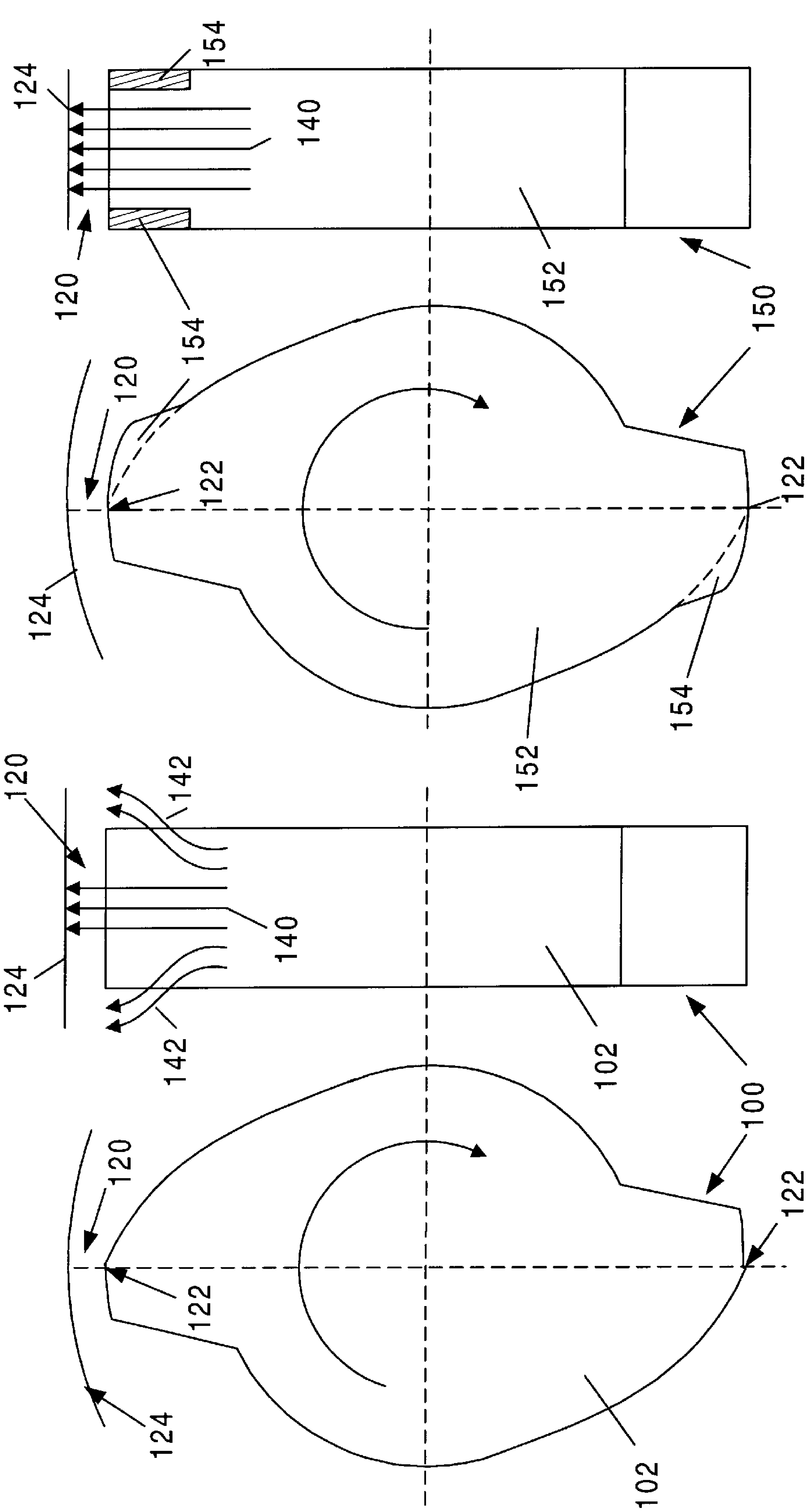


FIGURE 15A

FIGURE 15B

FIGURE 16A

FIGURE 16B

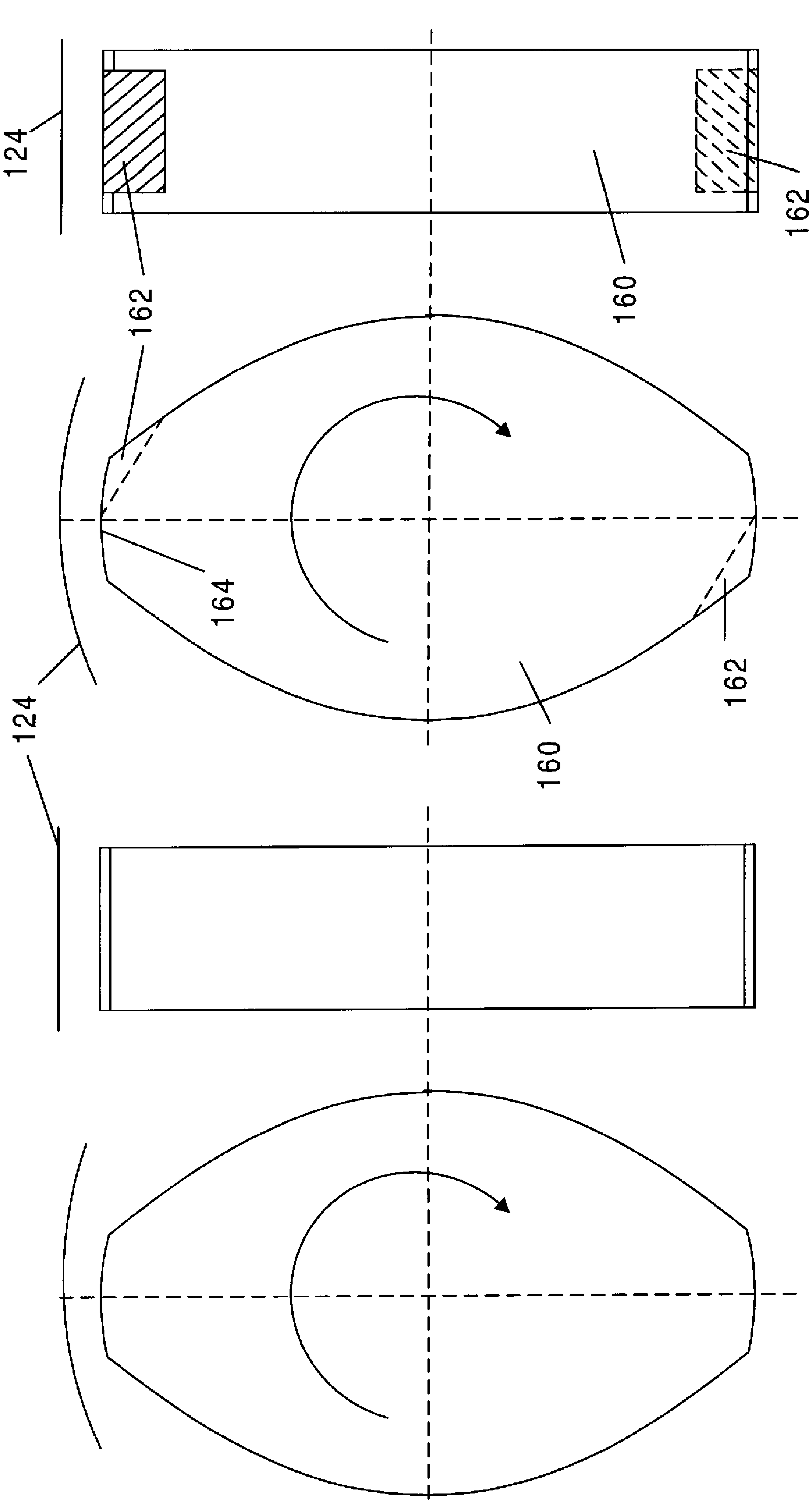
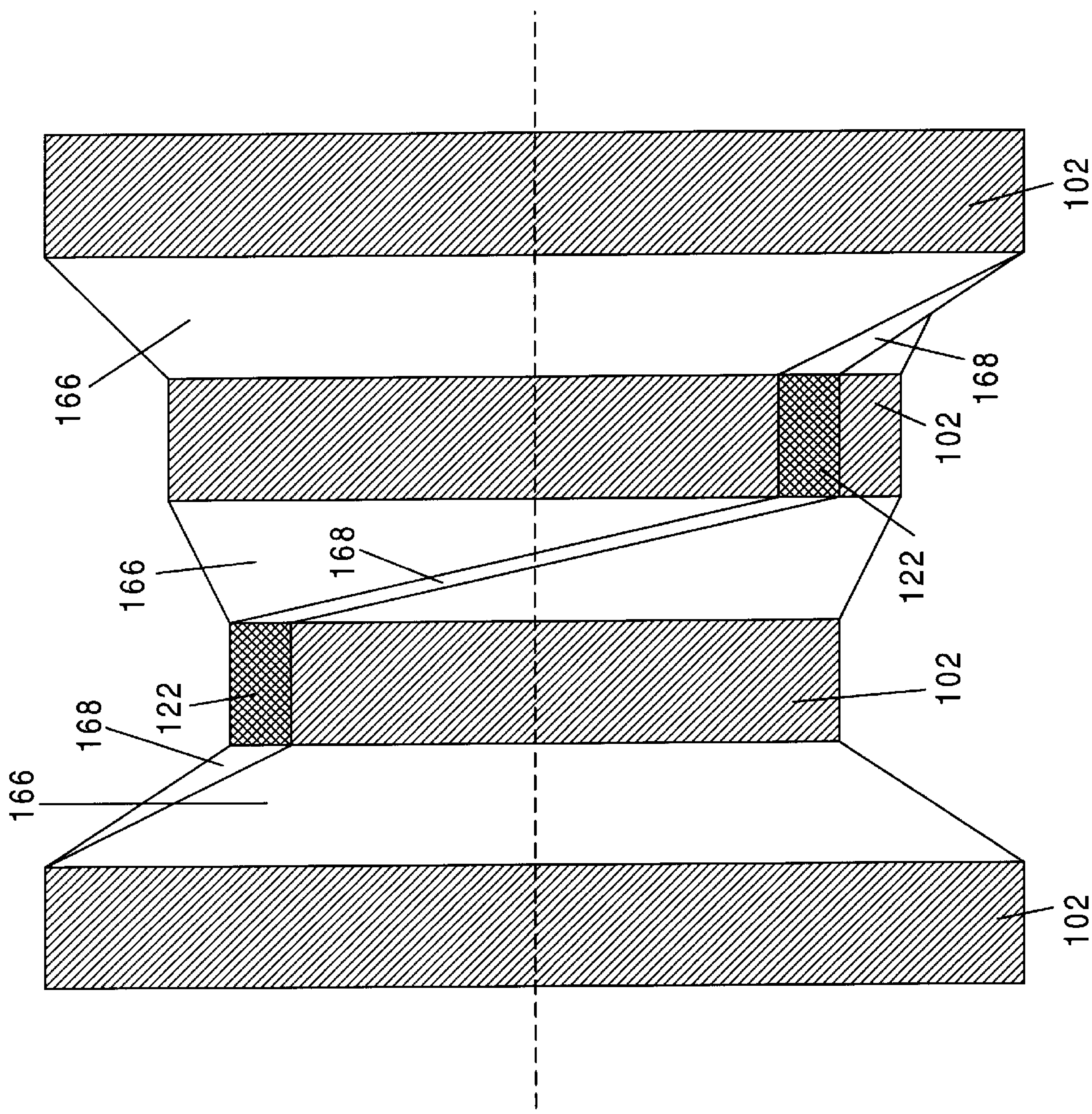


FIGURE 17A
Prior Art

FIGURE 17B
Prior Art

FIGURE 18A

FIGURE 18B



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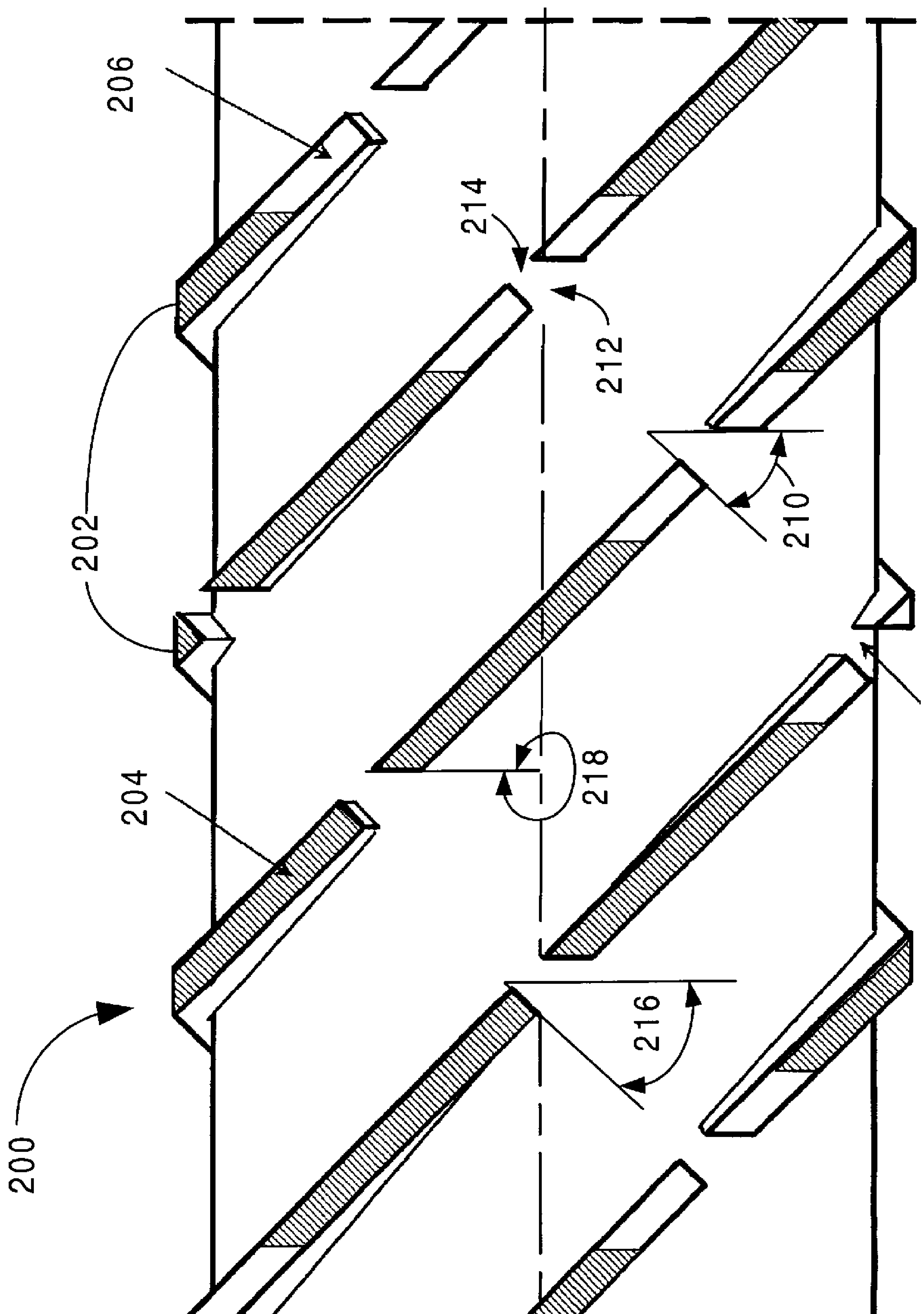

FIGURE 20

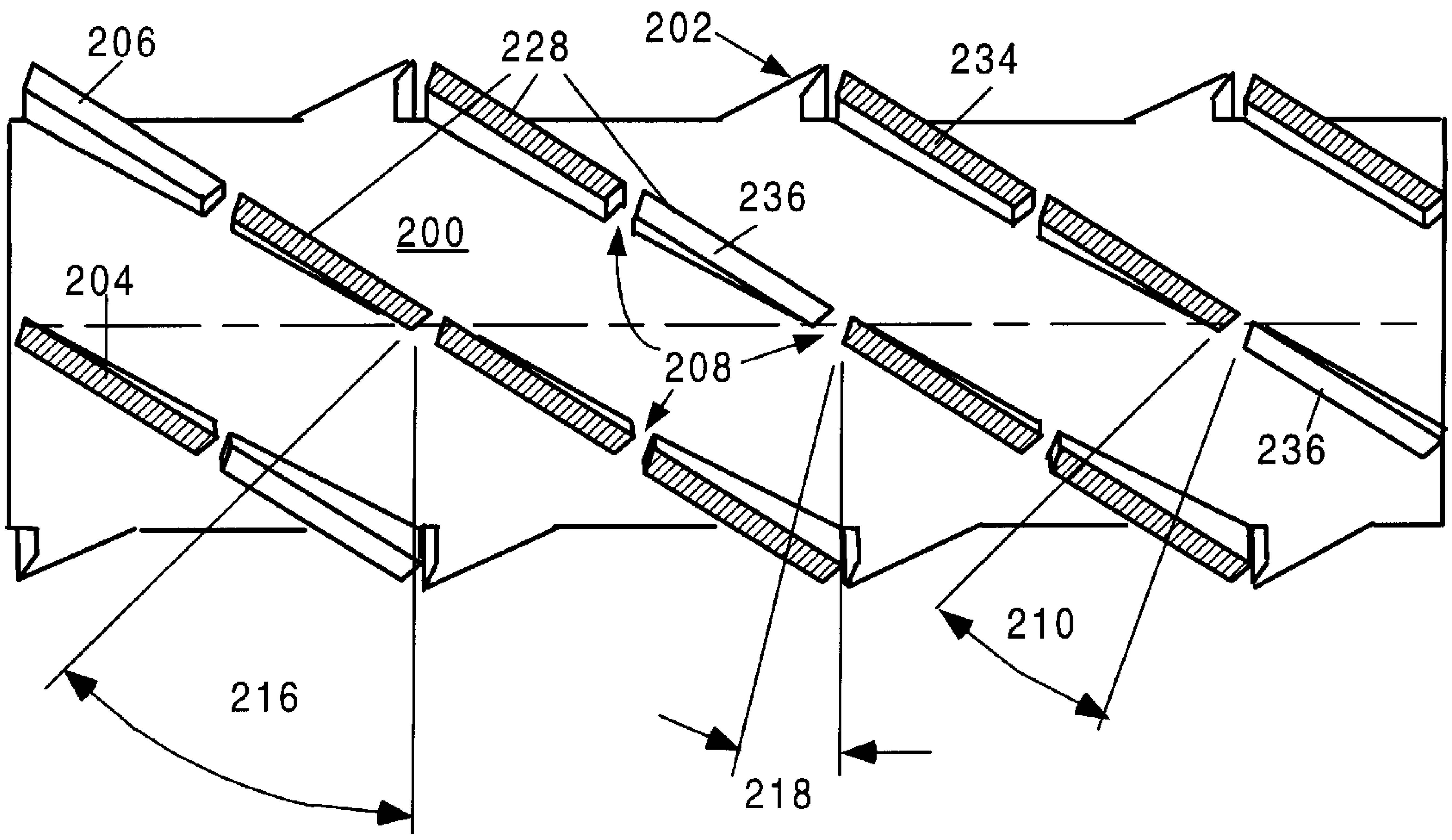

FIGURE 21

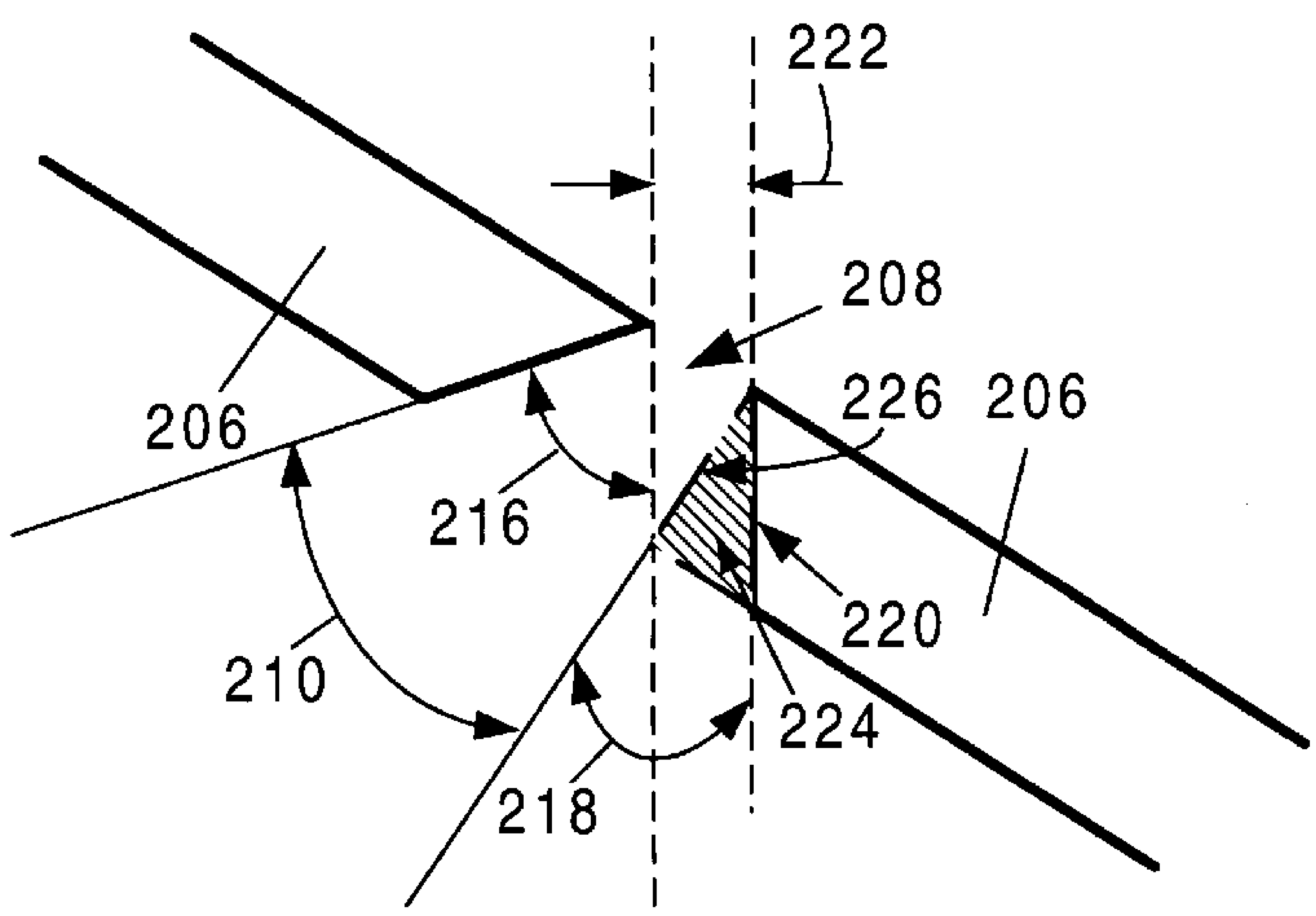

FIGURE 22

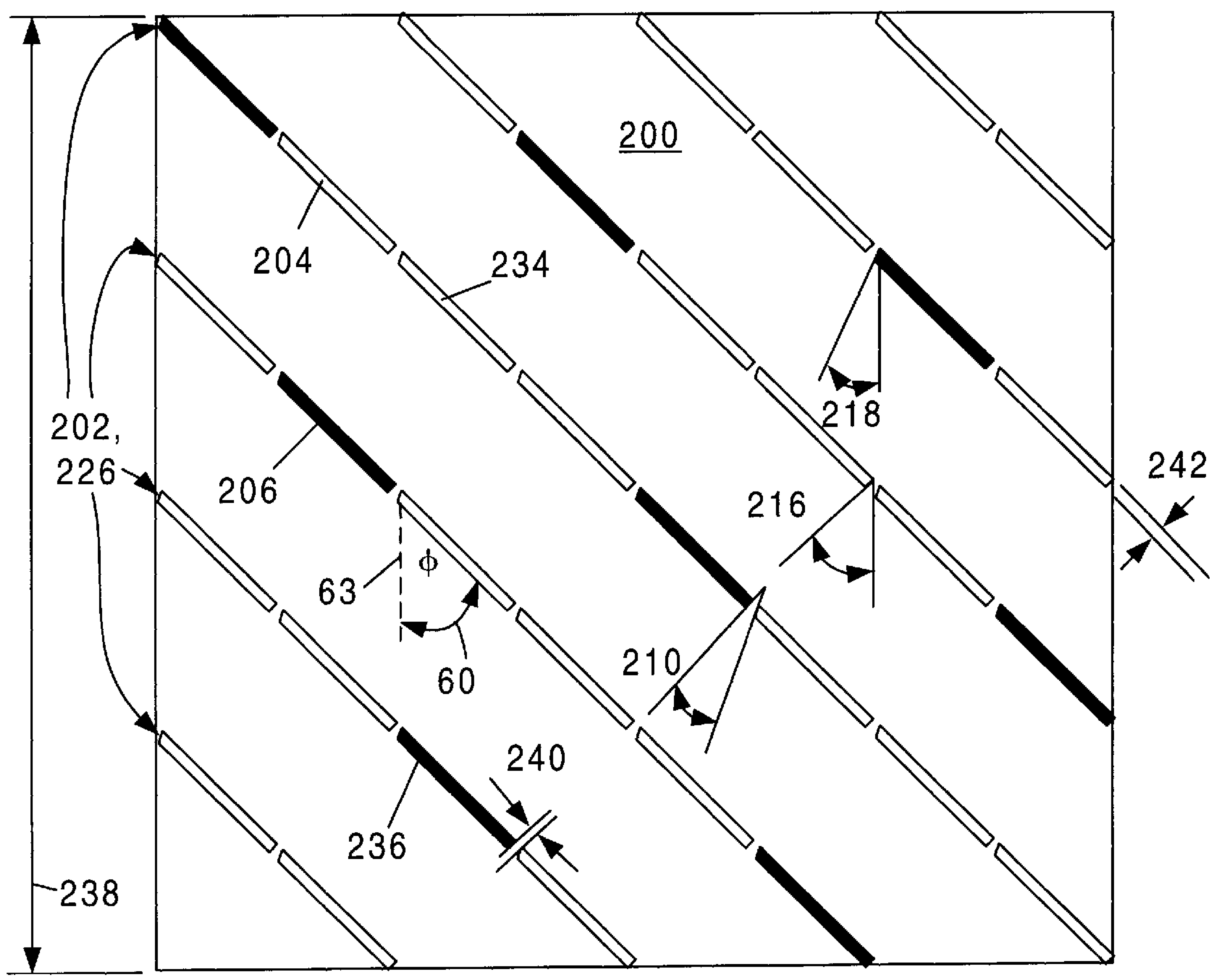

FIGURE 23

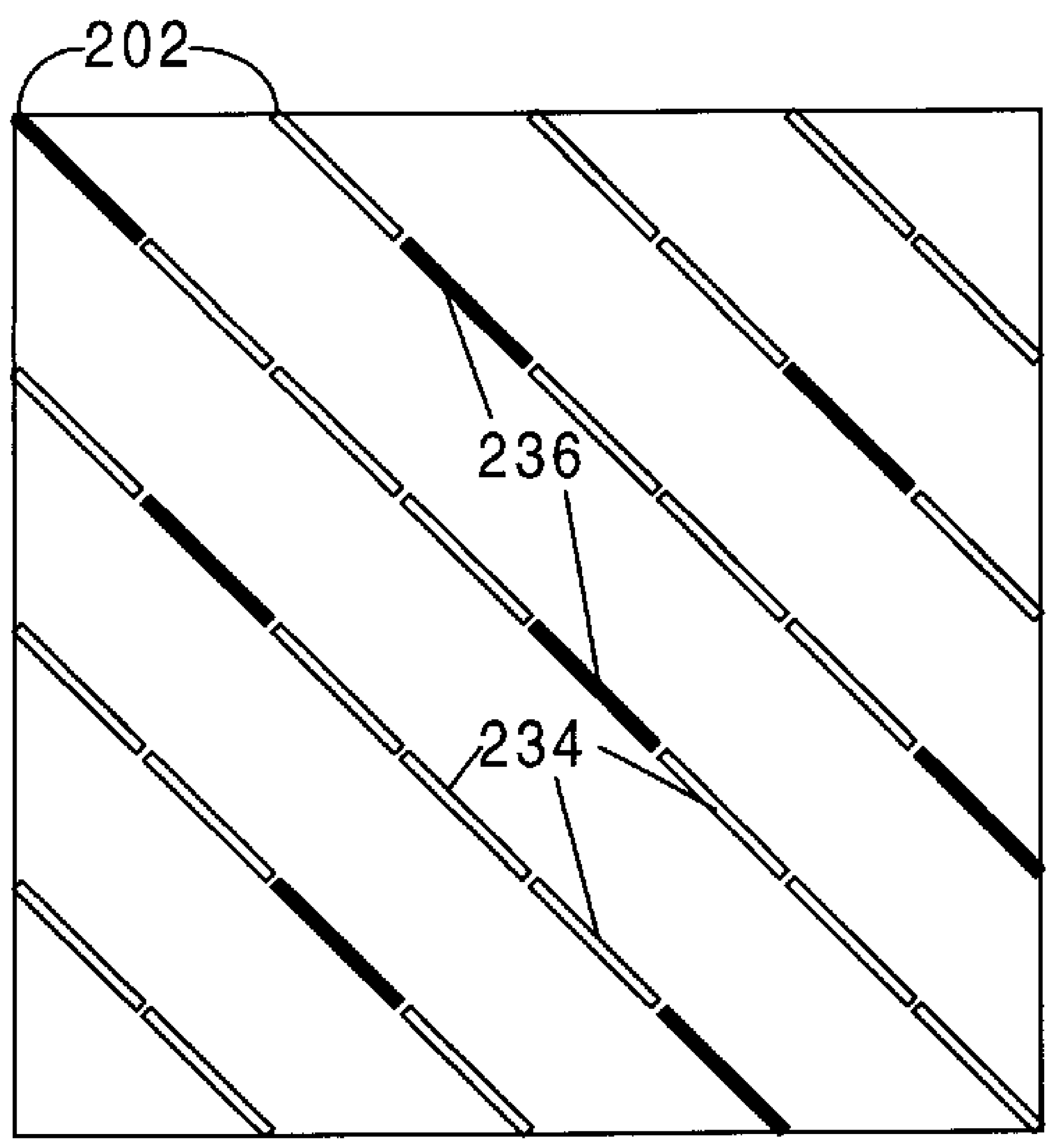

FIGURE 24A

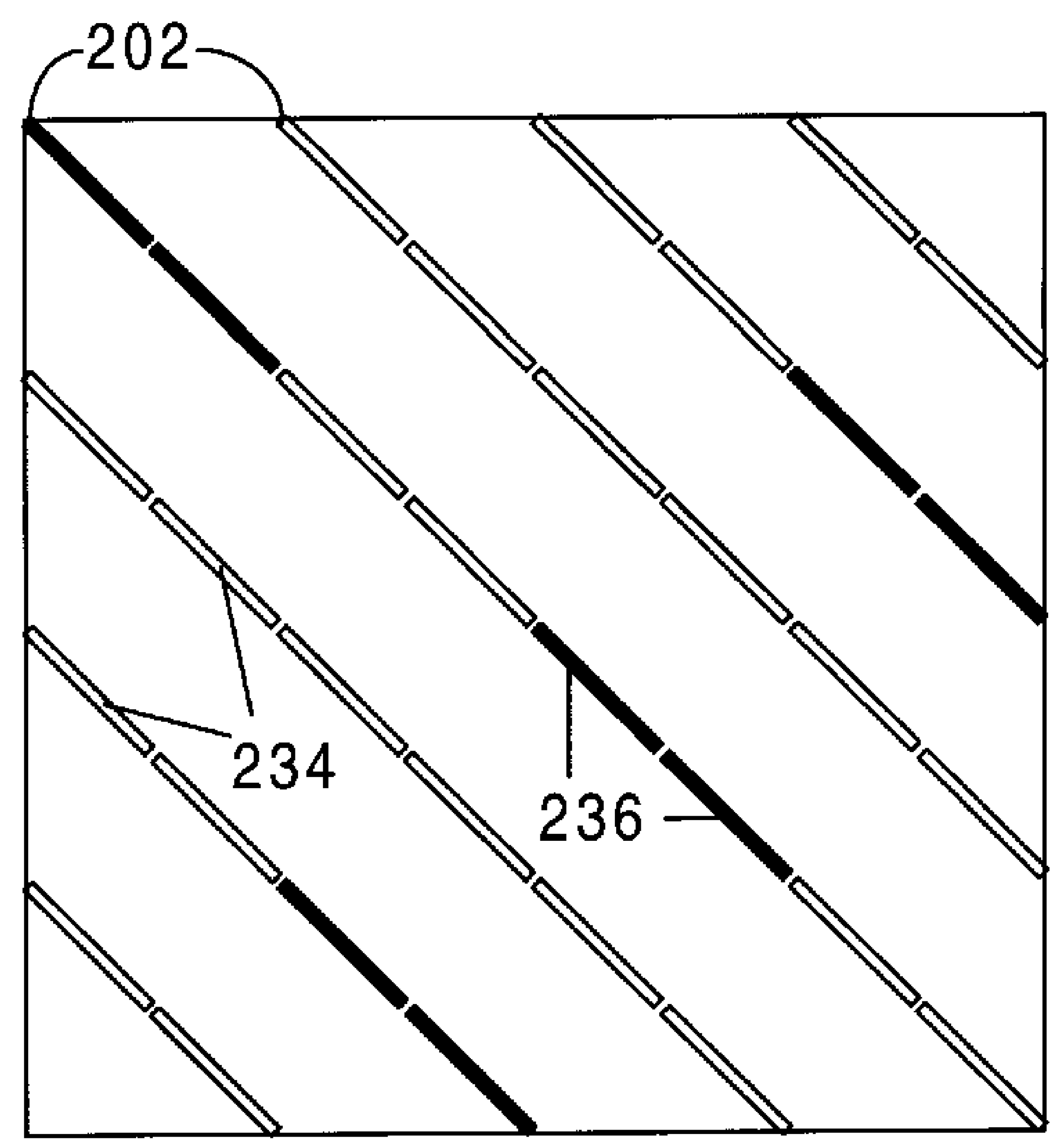

FIGURE 24B

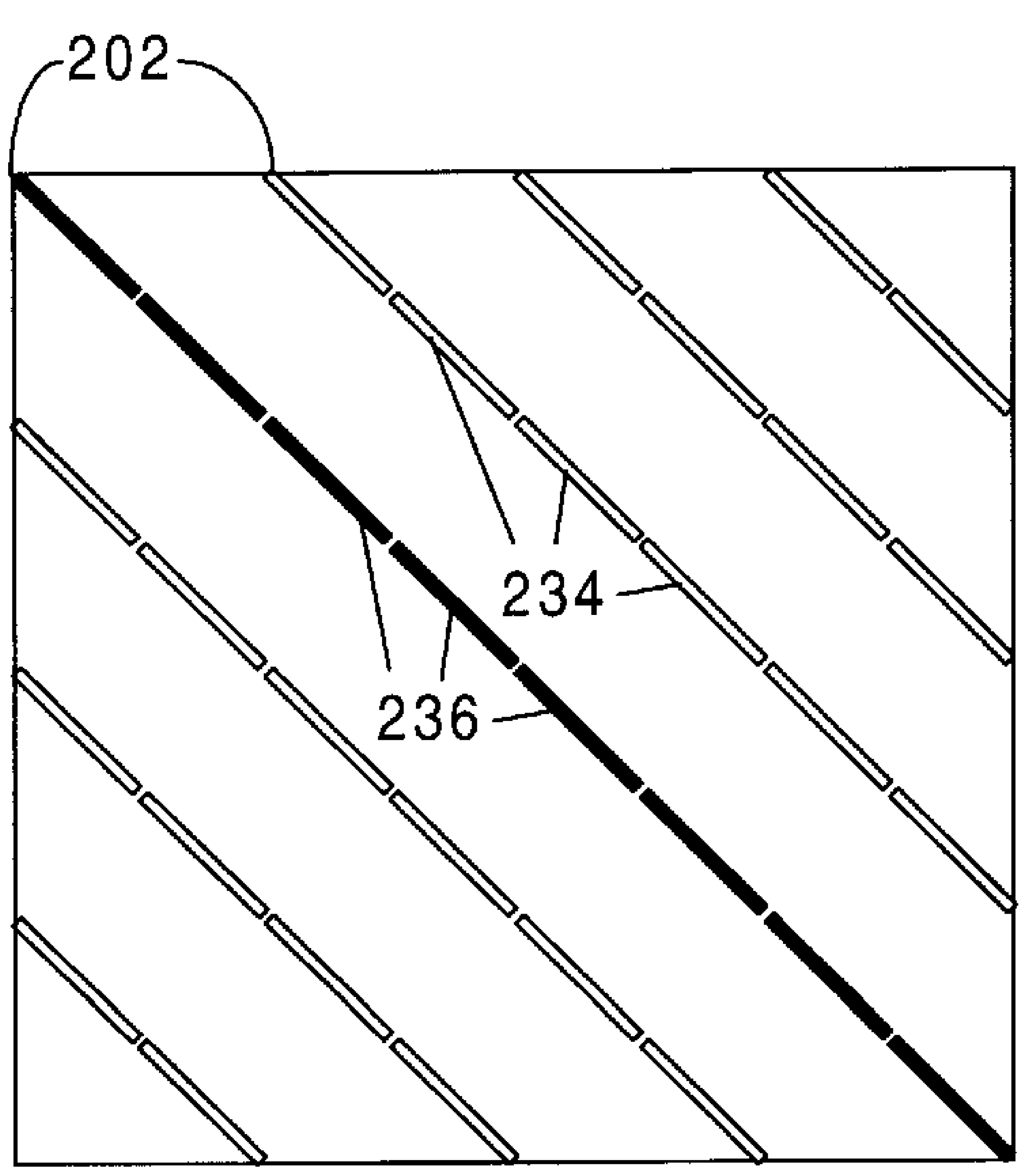

FIGURE 24C

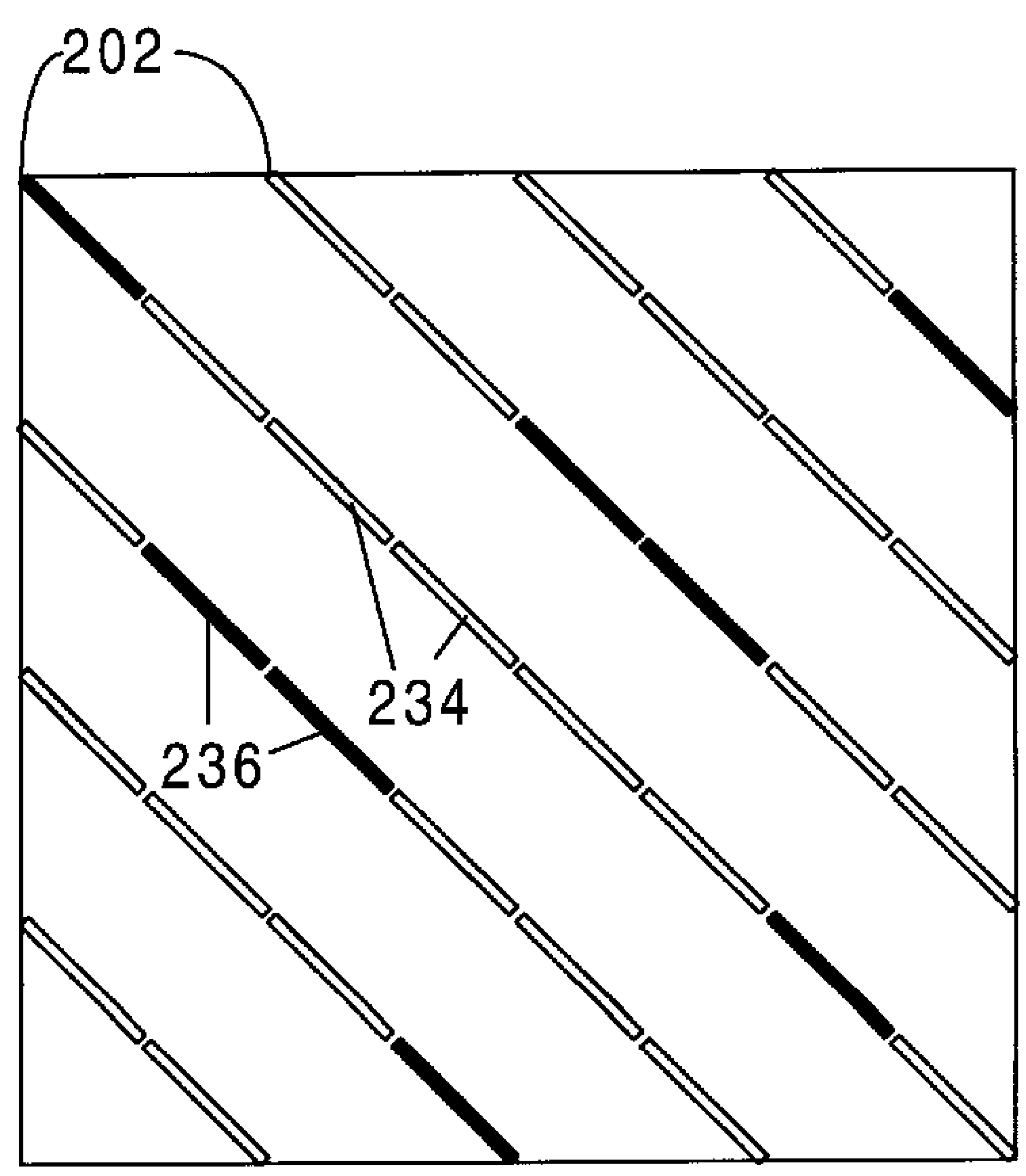

FIGURE 24D

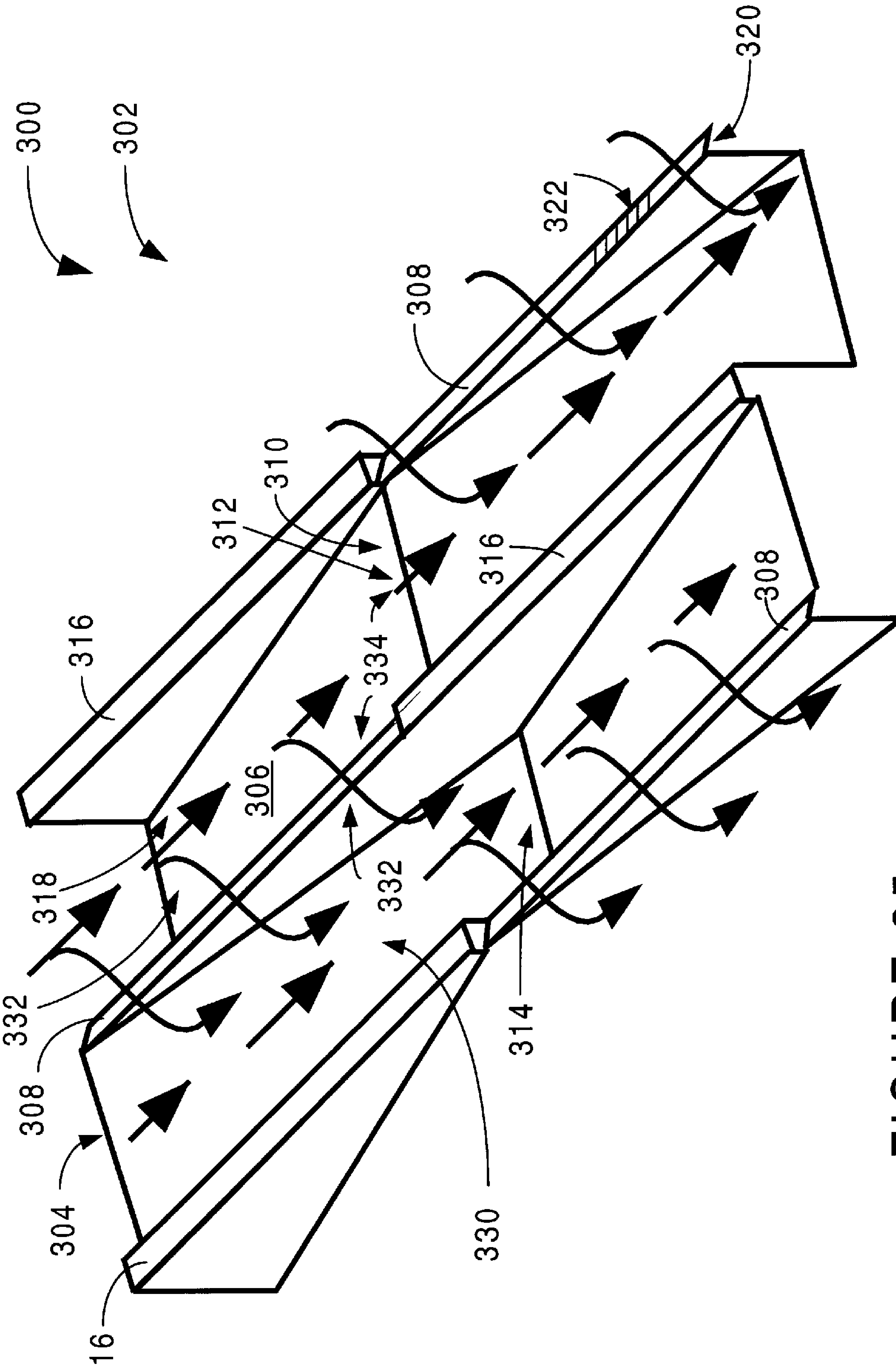
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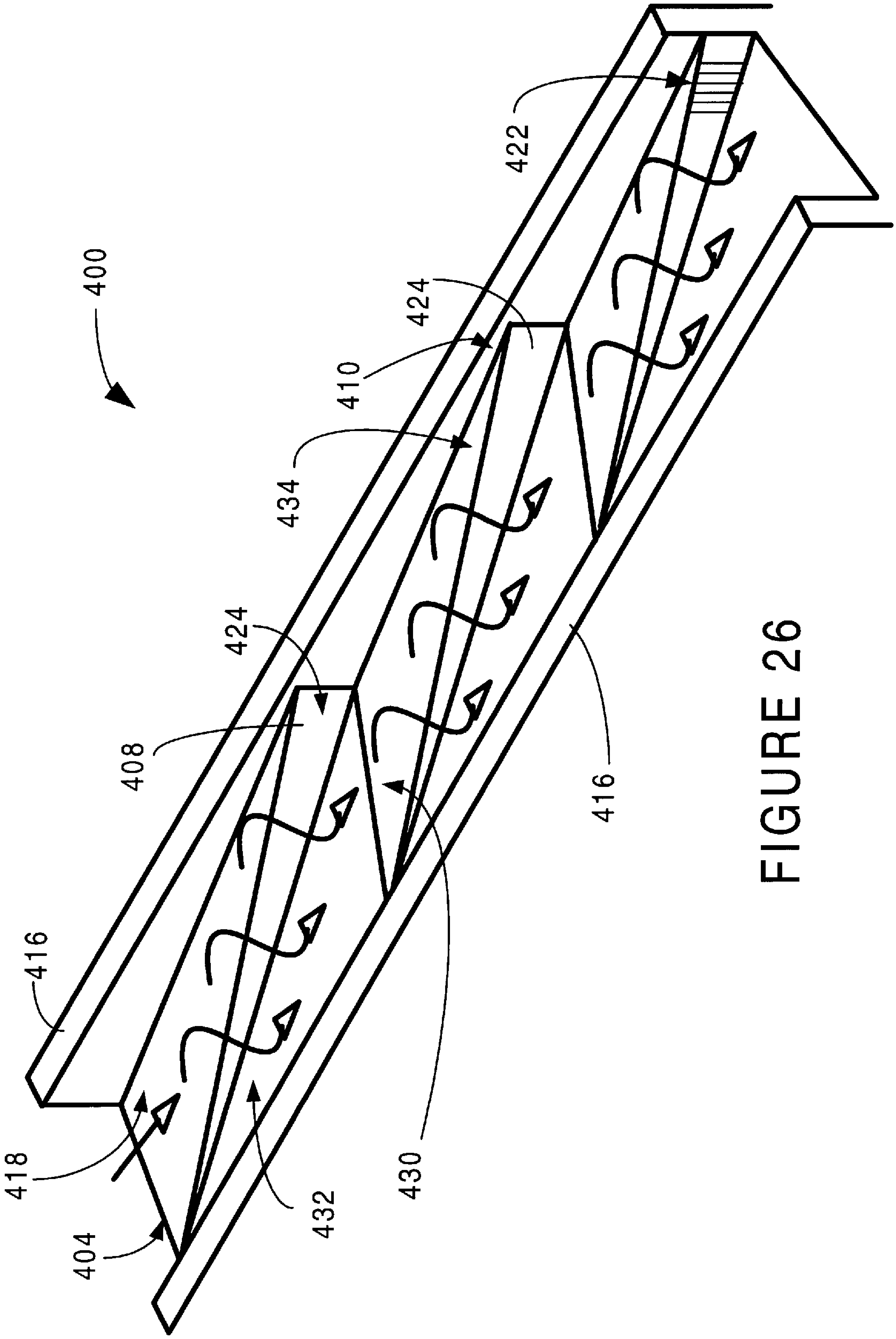
FIGURE 25



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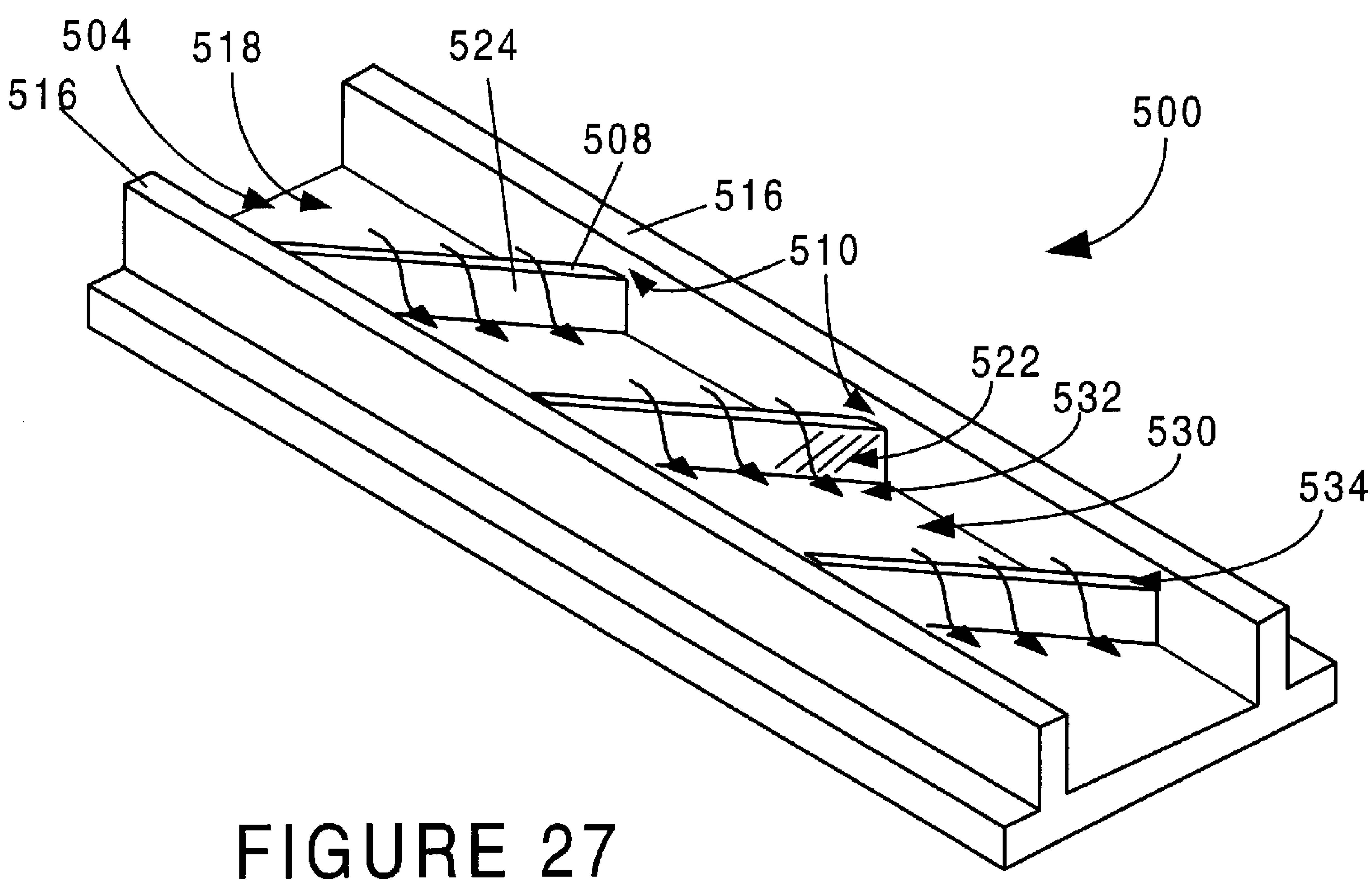

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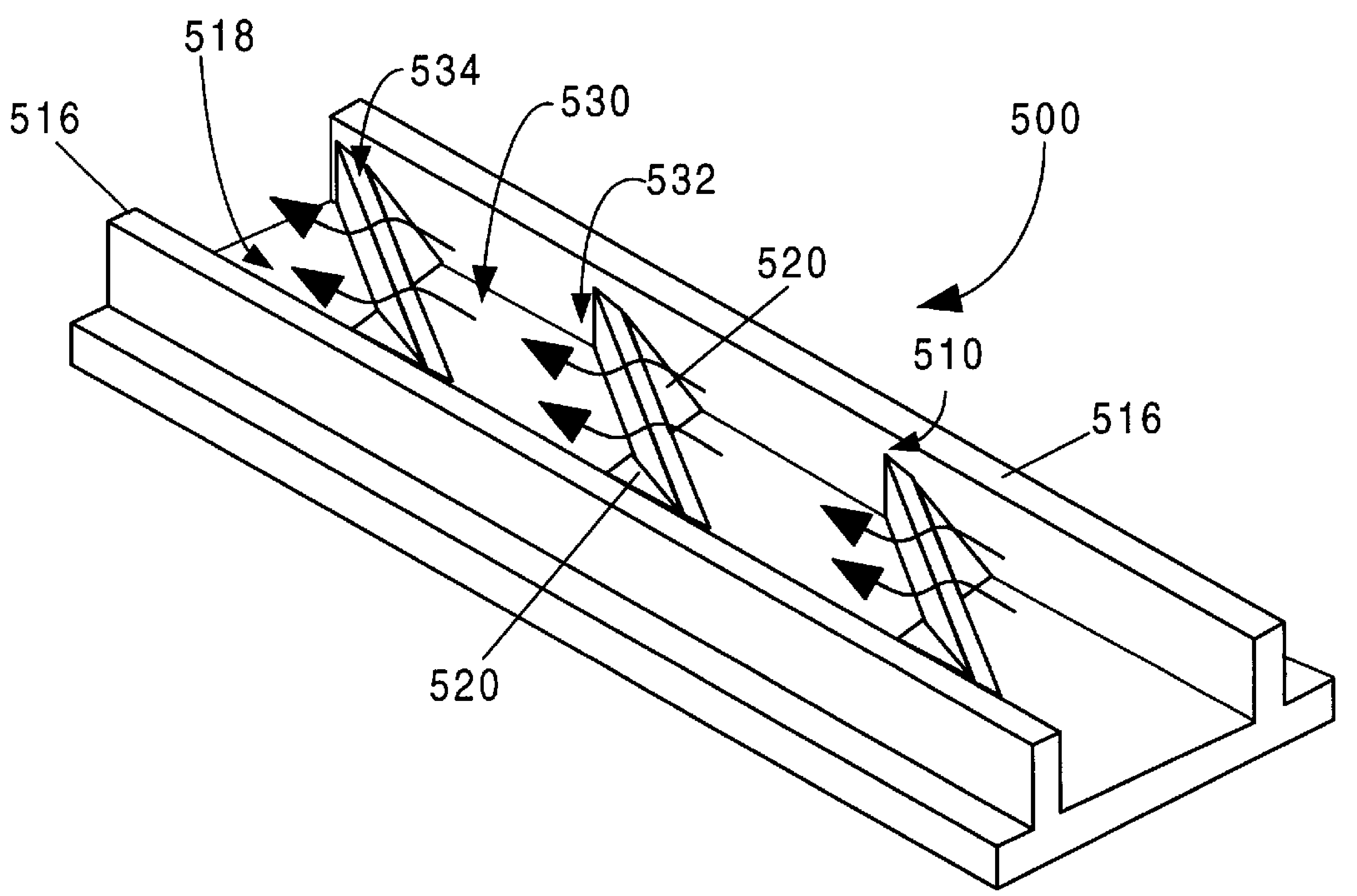


FIGURE 28

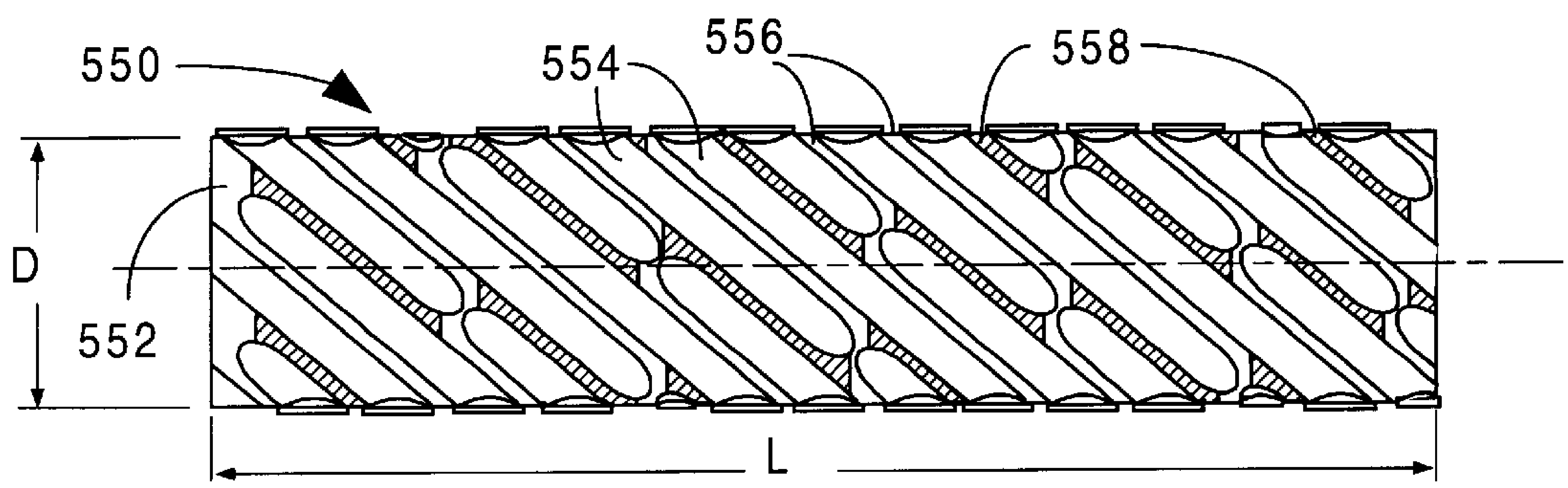


FIGURE 29

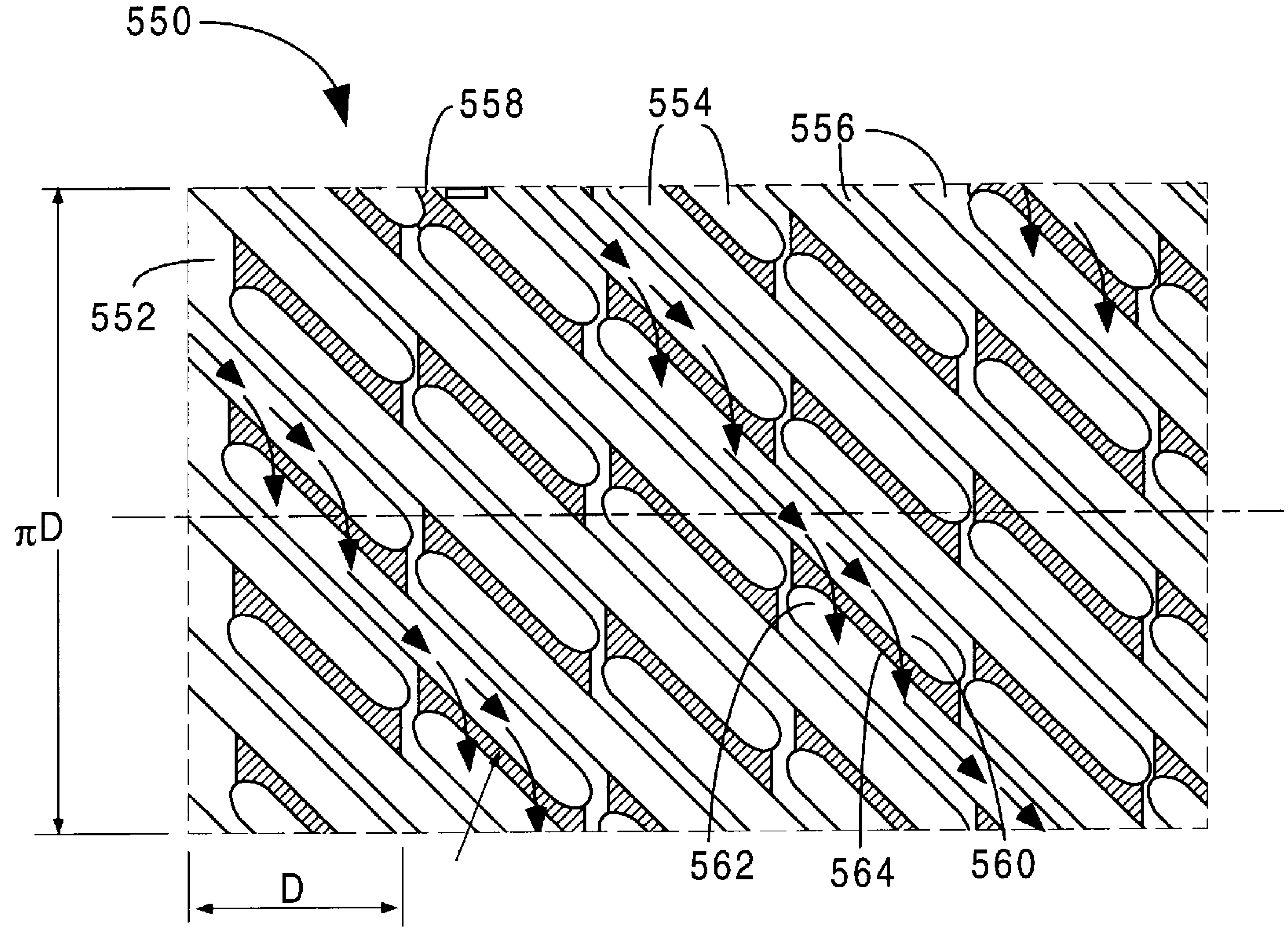
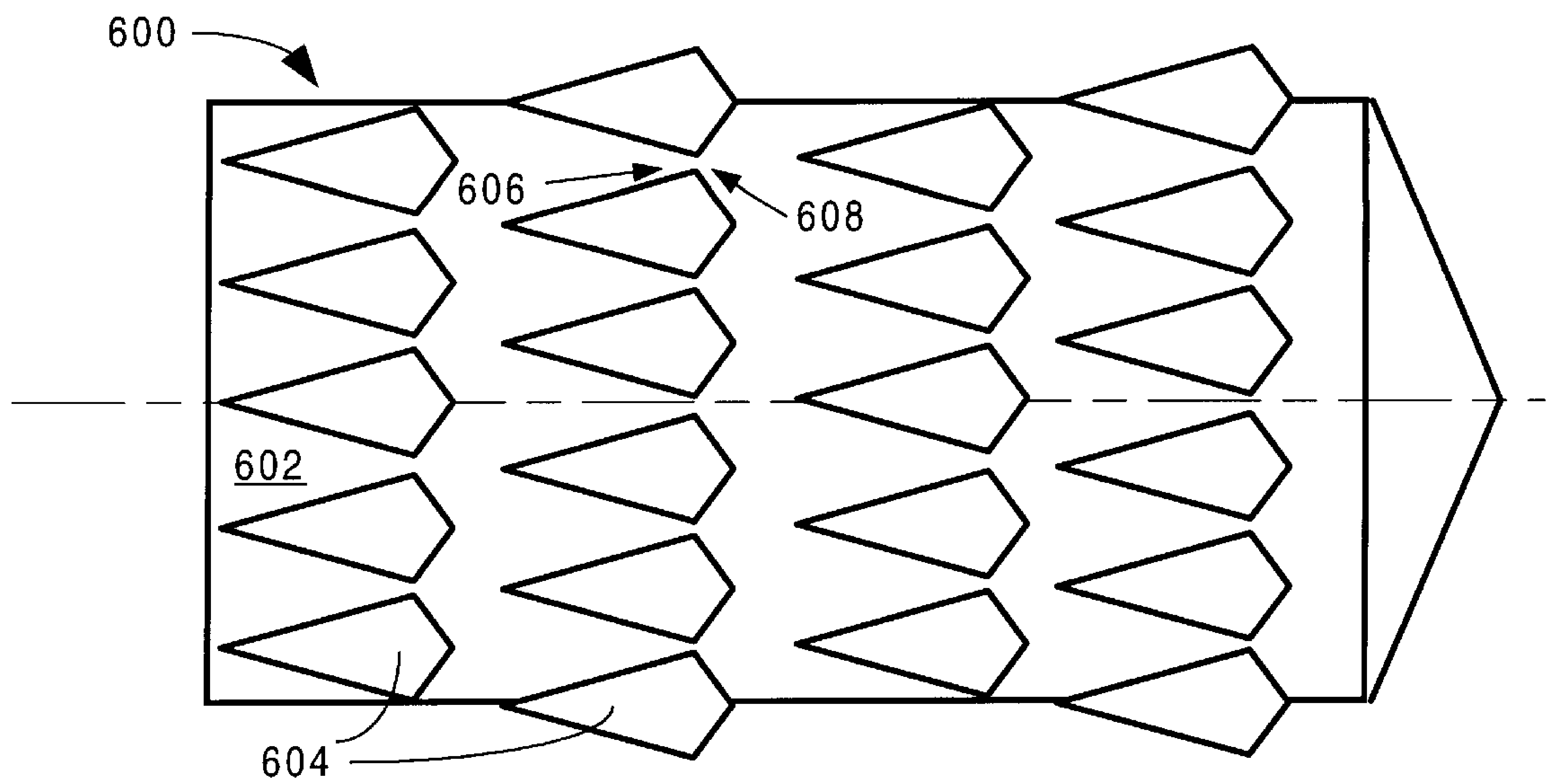


FIGURE 30



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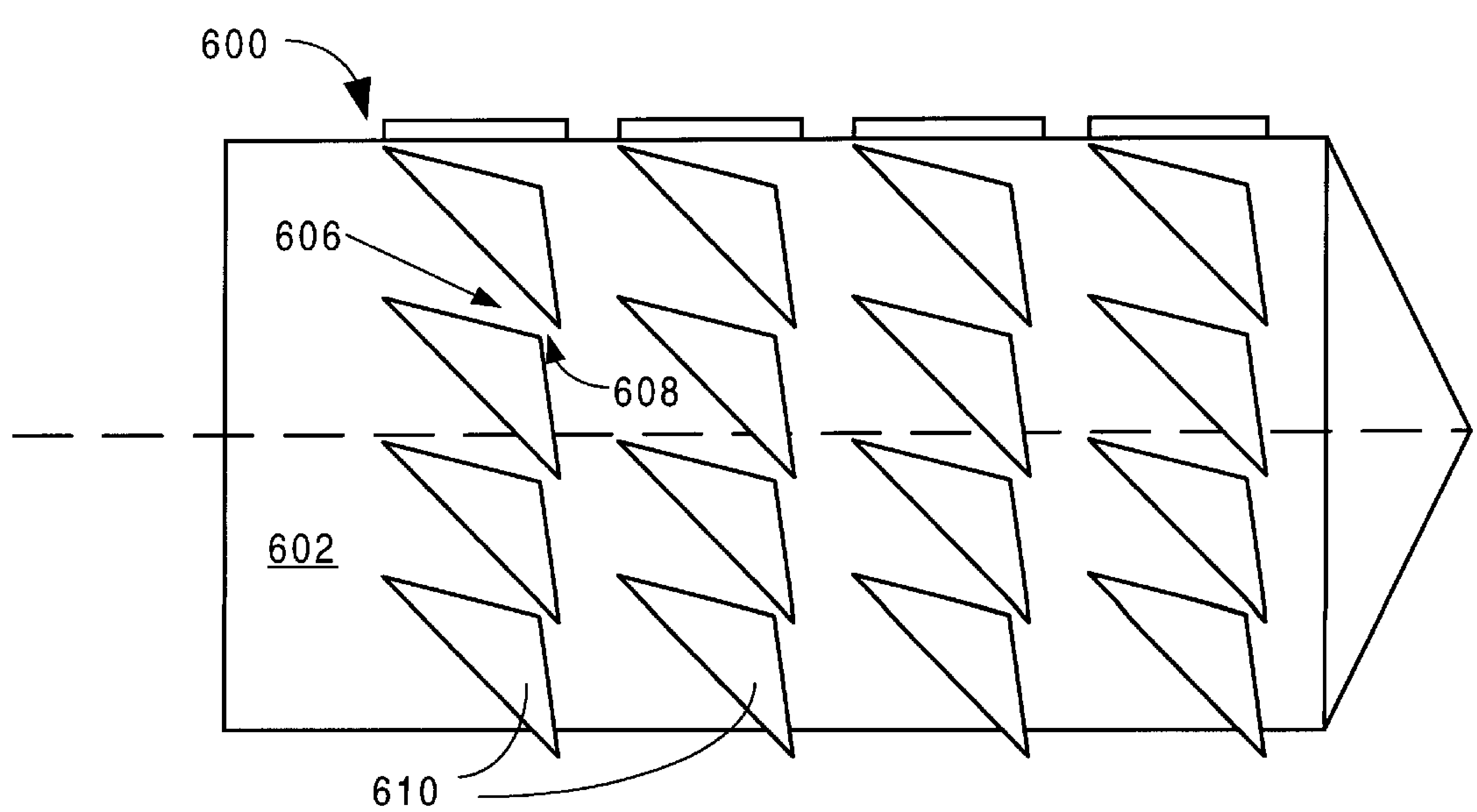

FIGURE 32

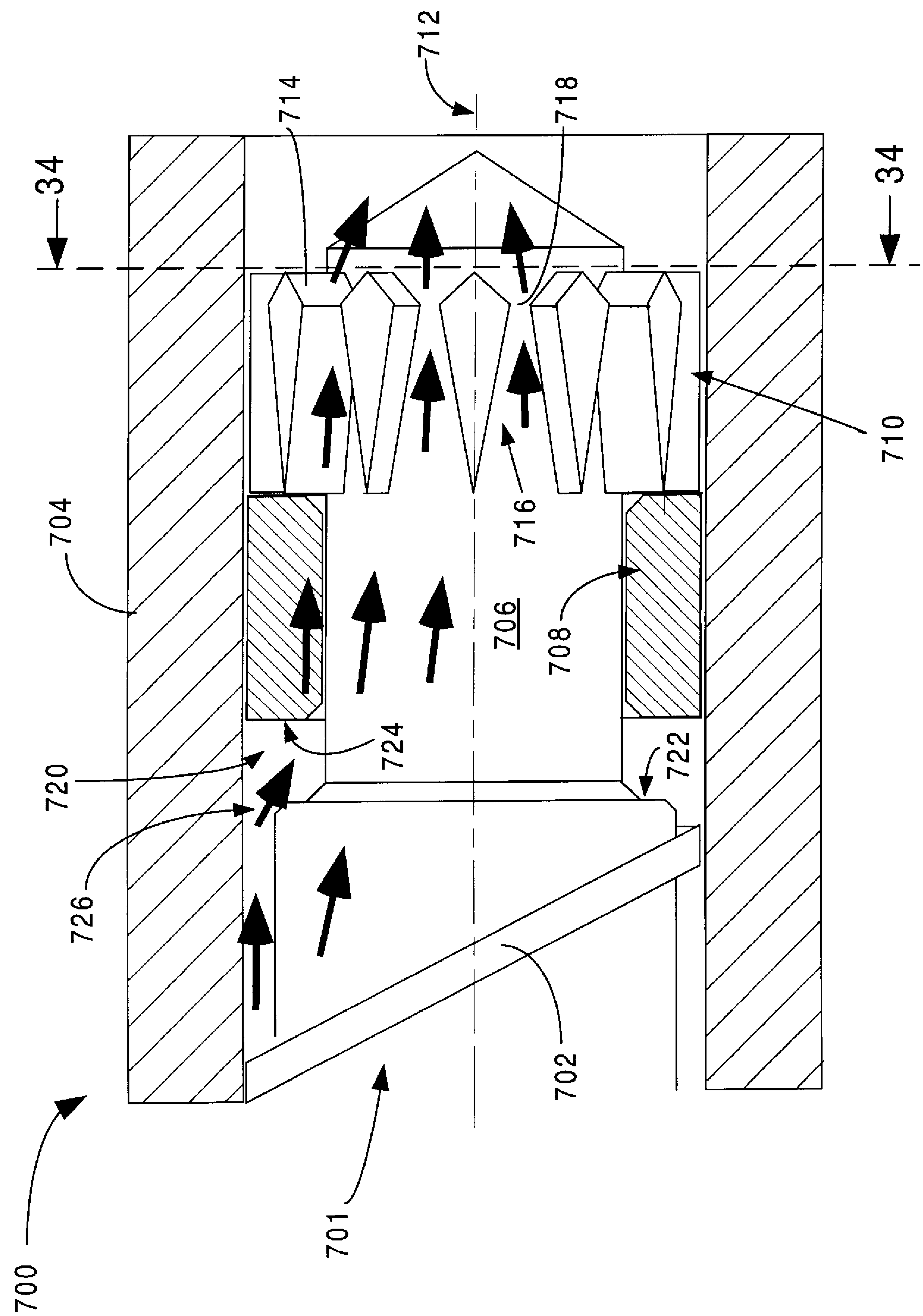

FIGURE 33

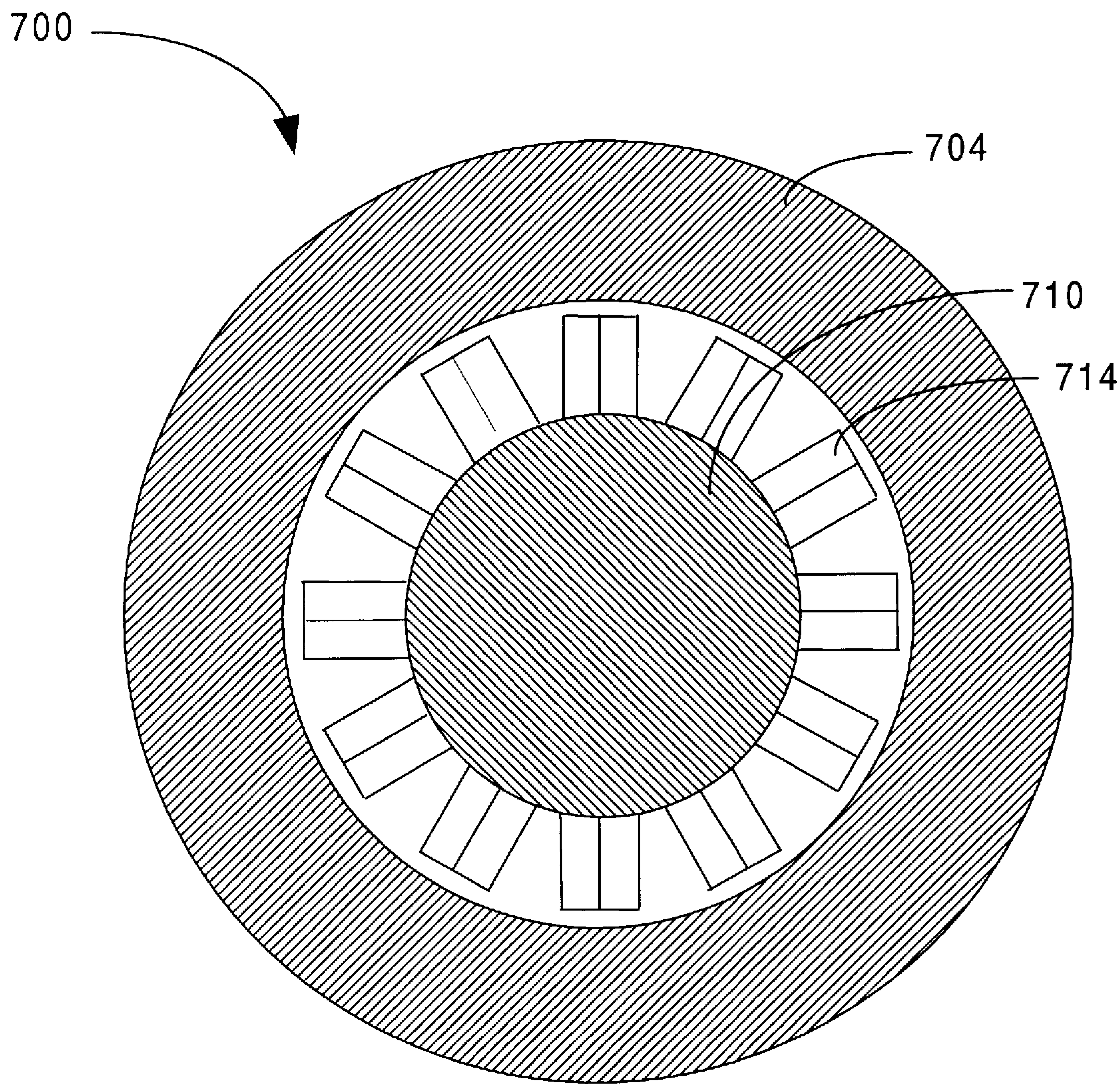

FIGURE 34

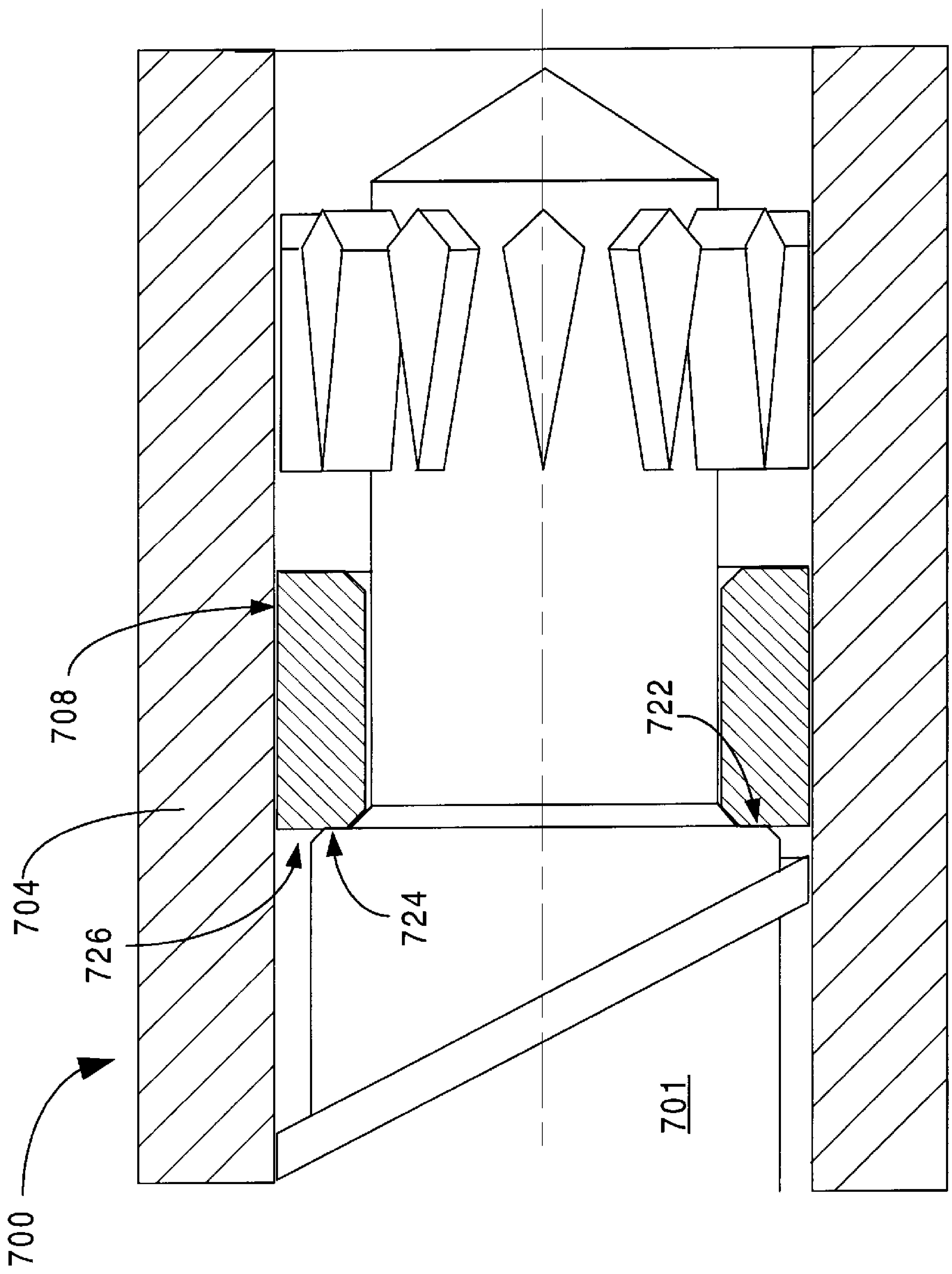

FIGURE 35

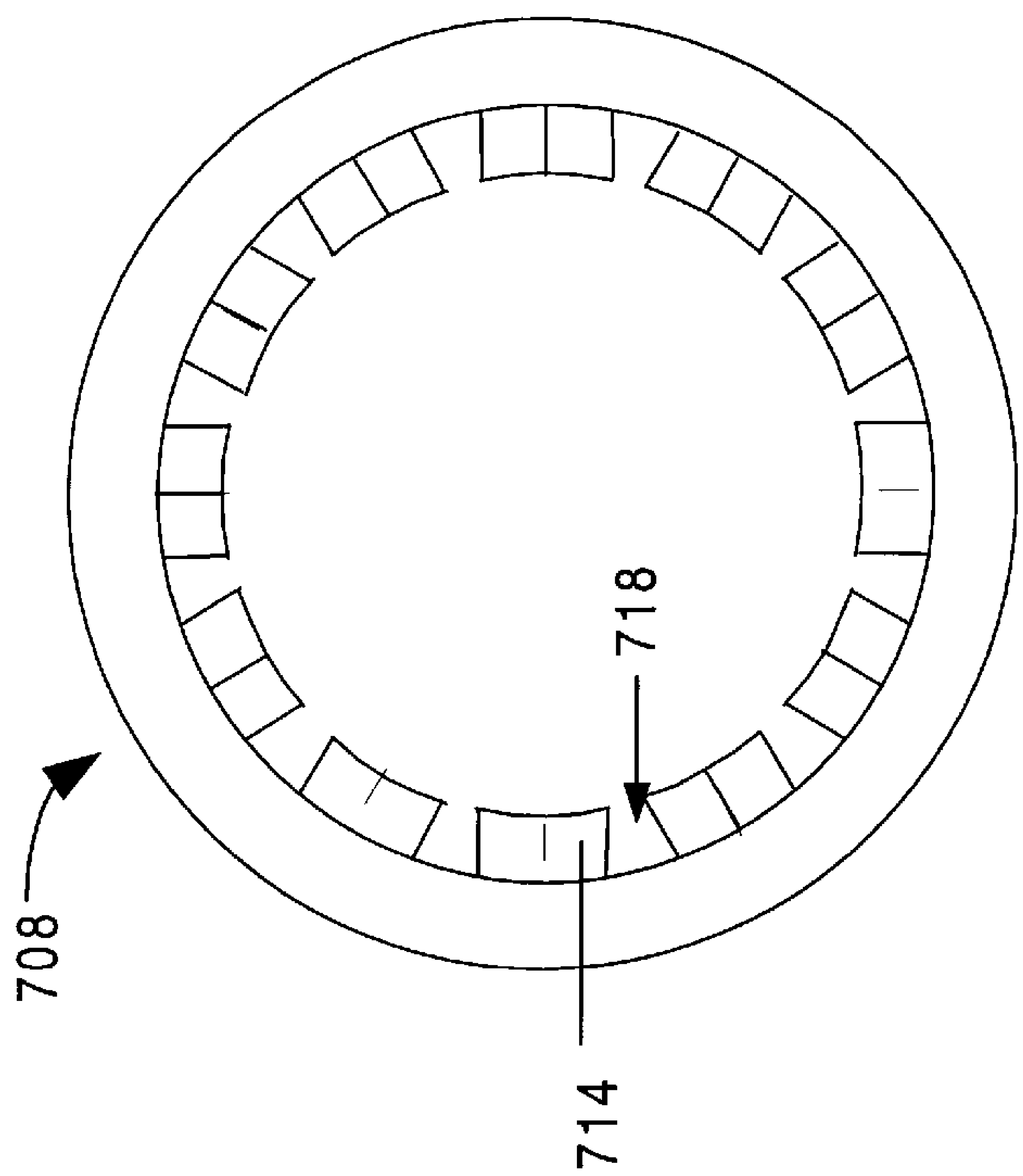

FIGURE 37

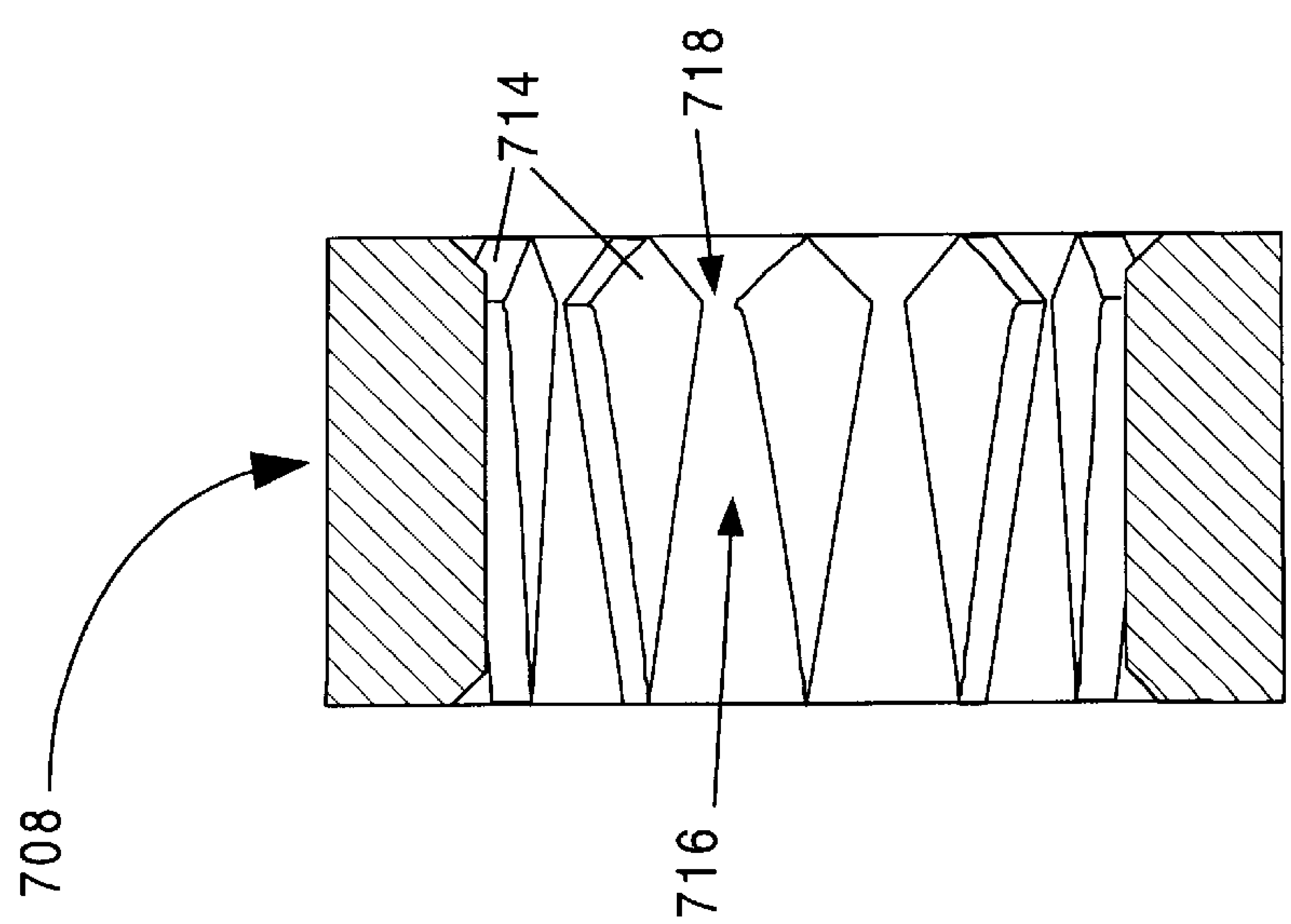

FIGURE 36

SCREW EXTRUDER WITH IMPROVED DISPERSIVE MIXING ELEMENTS

The following is a continuation-in-part of application 08/966,272 which was filed on Nov. 7, 1997, now U.S. Pat. No. 5,932,159.

TECHNICAL FIELD

The present invention relates generally to machines for extrusion of materials and more particularly to screw extruders adapted for use with plastics and plastic-like materials. The inventor anticipates that primary application of the present invention will be for the manufacture of color concentrates, polymer blends, and polymer alloys.

BACKGROUND ART

A screw extruder is a machine in which material, usually some form of plastic, is forced under pressure to flow through a contoured orifice in order to shape the material. Screw extruders are generally composed of a housing, which is usually a cylindrical barrel section, surrounding a central motor-driven screw. At a first end of the barrel is a feed housing containing a feed opening through which new material, usually plastic particles, is introduced into the barrel. The screw contains raised portions called flights having a larger radial diameter than the screw's central shaft and which are usually wrapped in a helical manner about the central shaft. The material is then conveyed by these screw flights toward the second end of the barrel through a melting zone, where the material is heated under carefully controlled conditions to melt the material, and then passes through a melt-conveying zone, also called a pumping zone. The melted plastic is finally pressed through a shaped opening or die to form the extrudate.

Besides conveying material toward the die for extrusion, the screw is depended upon to perform mixing of the feed material. Very generally, mixing can be defined as a process to reduce the non-uniformity of a composition. The basic mechanism involved is to induce relative physical motion in the ingredients. The two types of mixing that are important in screw extruder operation are distribution and dispersion. Distributive mixing is used for the purpose of increasing the randomness of the spatial distribution of the particles without reducing the size of these particles. Dispersive mixing refers to processes that reduce the size of cohesive particles as well as randomizing their positions. In dispersive mixing, solid components, such as agglomerates, or high viscosity droplets are exposed to sufficiently high stresses to cause them to exceed their yield stress, and they are thus broken down into smaller particles. The size and shape of the agglomerates and the nature of the bonds holding the agglomerate together will determine the amount of stress required to break up the agglomerates. The applied stress can either be shear stress or elongational stress and generally, elongational stress is more efficient in achieving dispersion than is shear stress. An example of dispersive mixing is the manufacture of a color concentrate where the breakdown of pigment agglomerates below a certain critical size is crucial. An example of distributive mixing is the manufacture of miscible polymer blends, where the viscosities of the components are reasonably close together. Thus, in dispersive mixing, there will always be distributive mixing, but distributive mixing will not always produce dispersive mixing.

In extrusion processes, the need for good dispersive mixing is often more important than for distributive mixing.

This is particularly true in the extrusion of compounds which contain pigments which must be uniformly mixed or small gage extrusion such as spinning of fibers or extrusion of thin films.

In screw extruders, significant mixing occurs only after the polymer has melted. Thus, the mixing zone is thought of as extending from the start of the melting zone to the end of the extrusion die. Within this area there will be considerable non-uniformities in the intensity of the mixing action and the duration of the mixing action, both in the barrel section and in the extrusion die. In molten polymer, the stress is determined by the product of the polymer melt viscosity and rate of deformation. Therefore, in general, dispersive mixing should be done at as low a temperature as possible to increase the viscosity of the fluid, and with it, the stresses in the polymer melt.

Fluid elements are spoken of as having a "mixing history", which refers to the amount of elongational and shear stress to which it has been exposed, and the duration of that exposure. A polymer element that melts early in the mixing zone process will have a more significant mixing history than one that melts near the end of the melting zone.

Generally, in an extruder with a simple conveying screw the level of stress or the fraction of the fluid exposed to it is not high enough to achieve good dispersive mixing. Distributive mixing is easier to achieve than dispersive mixing, but unmodified screws have also been found to produce inadequate distributive mixing for many applications. Therefore, numerous variations in screw design have been attempted in prior inventions to increase the amount of distributive or dispersive mixing in screw extruders. These devices usually contain a standard screw section near the material input hopper, and one or more specially designed sections to enhance mixing. These mixing sections naturally fall into the categories of distributive and dispersive mixing elements.

Varieties of distributive mixing elements are shown in FIGS. 2A–F. Practically any disruption of the velocity profiles in the screw channel will cause distributive mixing. Thus even simple devices, such as the placement of pins (see FIG. 2A) between the screw flights can enhance distributive mixing. FIG. 2B shows the well-known Dulmage mixing section, in which the polymer flow is divided into many narrow channels, which are combined and divided again several times. The Saxton mixing section (FIG. 2C) and the "pineapple" mixing section (FIG. 2D) are used to produce similar results. FIG. 2E shows a screw which has slots cut into the flights. A variation called the Cavity Transfer Mixer is shown in FIG. 2F. There are cavities both in the rotor and the barrel. This type of device reportedly performs both dispersive and distributive mixing.

In addition to these devices, static mixers are often used to divide and recombine the melt stream to intermingle the material and eliminate variations in temperature, composition and mixing history. These generally do not provide regions of high stress, and are thus mostly used for distributive mixing.

The devices shown in FIGS. 2A–F have been primarily classified as distributive mixers because their action is mainly to spatially redistribute material without subjecting it to regions of high shear stress. The variations shown in FIGS. 2G–J are designed to include high shear stress regions and thus perform dispersive mixing.

The most common dispersive mixing section is the fluted or splined mixing section in which one or more barrier flights are placed along the screw so that material has to flow over them. In passing through the barrier clearance, the material is subjected to a high shear rate which acts to break up agglomerates. One such device is the Maddock mixing section, which is shown in FIG. 2G. The Maddock has longitudinal splines that form a set of semicircular grooves. Alternate grooves are open on the upstream and downstream ends. Material that enters the inlet grooves is forced to pass over the mixing flights, which are shown as cross hatched areas, before reaching the outlet grooves. While passing over the mixing flights, the material is subjected to high shear stress. The disadvantage of this type of mixing element is that it reduces the pressure at the output side of the mixing section and thus reduces the output of the extruder. Also there may be regions in which material may stagnate since the grooves have constant depth in a longitudinal direction. This makes it less suitable for materials of limited thermal stability.

FIG. **2**H shows the Egan mixing section, which has splines that run in a helical direction to form channels separated by mixing barriers. These channels can have a gradually reducing depth, tapering to zero depth at the end of the mixing section, which reduces the chance of stagnation points. This helical design consumes less pressure than the Maddock style, thus producing less reduction in extruder output.

A blister ring, shown in FIG. **2**J, is simply a cylindrical section on the screw that has a small radial clearance, through which all material must pass. This can cause a large pressure drop on the output side of the blister ring, resulting in a significant reduction in overall extruder output.

FIG. **2**K reproduces in part FIG. **2** from U.S. Pat. No. 5,356,208 to Tadmor. A portion of the screw surface **33** gradually increases in a radial distance, making a smooth transition to radial maximum at the tip **50**. This tip **50** is also rounded and the screw surface **33** then gradually and smoothly decreases in radius to a minimum near the leading wall **58** of a scraping flight **75**. The entire cycle from radial minimum through maximum and back to minimum takes place in nearly 180 degree of angular rotation. This increase in the radial distance of the screw surface portion has the necessary effect of decreasing the depth of the screw channel. The volumetric capacity of the screw extruder is decreased when the channels are decreased in depth, thus efficiency of output is reduced. Also, although the Tadmor invention may produce some shearing action at the tips, there is no strong elongational flow due to the very gradual reduction in channel depth. As discussed above, elongational stress is much more efficient than shear stress in breaking down agglomerates of material. The Tadmor invention also uses a conventional helix angle of 17–18 degrees. As will be discussed later, the present invention preferably uses a much larger helix angle, which produces much more effective dispersive mixing and much higher output.

Screw extruders can have more than one central screw. Twin-screw extruders may operate with two screws that may either rotate in the same direction, or they may be counter-rotating. There are some machines that use more than two screws.

In counter-rotating twin-screw extruders, dispersive mixing primarily occurs in the intermeshing region between the screws. This action is similar to that in a two-roll mill. This configuration has the disadvantage that the mixing action creates substantial separating forces on the screws. These forces can push the screws against the barrel, if these forces grow too great. This can cause wear on the screws and the barrel, thus the screw speed has to be kept low, with resulting decrease in the throughput of the extruder.

In intermeshing co-rotating twin-screw extruders, the screw surfaces in the intermeshing region move in opposite directions. As a result, most of the material bypasses the intermeshing region and moves from one screw to the other repeatedly.

Some twin screw machines have kneading blocks included to increase dispersive mixing. These kneading blocks are most commonly flat paddles of roughly elliptical shape which are stacked on a central shaft, but offset at varying angles. Each paddle on the shaft is paired with a corresponding paddle on the second shaft. The shafts usually both rotate in the same direction but with the angular orientation of the paddles staggered at a certain angle. We can consider the elliptical paddle shapes to have a major and a minor axis with a "tip" on each end of the major axis and a "mid-point" at each end of the minor axis. At one point in the rotation cycle, a tip of a paddle on the first shaft, when horizontally oriented, will nearly contact the midpoint of a paddle on the second shaft, whose tip will then be vertical. As this second, vertical tip rotates towards horizontal, the first tip traces along the elliptical outline of the second paddle, thus "wiping" it. At a further point in the rotation cycle, the second paddle wipes the outline of the first. This wiping action keeps material from stagnating or collecting on the paddle edges. It also imposes constraints on the shapes of the paddles, as the travel of the tip of the neighboring paddle defines the outline of the paddle itself. Although this configuration of paddles can produce fairly good elongational stress in material, the above constraint on the shape of the paddles prevents variations in design, which may produce even better elongational stress regions.

In general, twin-screw extruders are considered to be better at dispersive mixing than single-screw extruders. However for a given capacity, multi-screw machines are usually considerably more costly than single-screw extruders.

For improved mixing to occur, there are several important aspects to be considered. In dispersive mixing, it is the passage of material through a region of high stress that produces the desired breakdown of agglomerates. A single pass through a high stress region will likely achieve only a single rupture of the agglomerate. To achieve a fine scale of dispersion, multiple passes and ruptures ay be necessary. Also, for efficient dispersive mixing, stresses in the high stress region should have a strong elongational component, as well as a shear component. For efficient operation of the extruder as a whole, a low pressure drop across the mixing section is desirable. It is also important to combine dispersive and distributive mixing to achieve a more uniform overall mixture. Some distributive mixing occurs whenever dispersive mixing is done, but by deliberately combining distributive elements with the dispersive elements, chances are improved that all fluid elements will pass through the high stress region, preferably many times, for proper dispersion.

To make sure that all agglomerates and droplets pass through high stress regions at least once, the flow rate through the high stress regions must be large enough compared to the overall forward flow rate. This can be done by designing the number of high stress regions, their length and the size of the gap through which material will pass. It is also preferable that there be more than one high stress region, and that these regions are symmetrically arranged around the circumference of any section along the length of the screw, so that forces will be balanced and the possibility of deflection of the screw will be minimized. To reduce pressure drop in the mixing section, it is desirable to have the high stress regions in a forward helical orientation, which can be done by a continuous forward helix or in a stepped forward helix with kneading disks.

Another consideration which makes improved dispersive mixing desirable, is that as the size of unmelted particles is reduced by better dispersive mixing, these particles are more easily melted. Thus if more efficient dispersive mixing can be generated in the melting zone of the extruder, it can speed up the melting process and the required length of the melting zone can be decreased. This would allow more compact and efficient extruders to be designed.

For the foregoing reasons, there is a great need for a screw extruder which provides better dispersive mixing than in presently available extruders.

DISCLOSURE OF INVENTION

Accordingly, it is an object of the present invention to provide a screw extruder which provides improved dispersive and distributive mixing.

Another object of the present invention is to provide a screw extruder in which material is repeatedly passed through regions of high stress for better break-down of agglomerates into smaller particles.

And, another object of the invention is to provide a screw extruder having a number of high stress regions which produce high elongational stress as well as shear stress.

Yet another object of the invention is to provide a single screw extruder which is less costly to manufacture for its capacity than a multi-screw extruder, but which provides dispersive mixing comparable or better than conventional multi-screw extruders.

A further object of the present invention is to provide a screw extruder in which the high stress regions do not produce a large pressure drop which may impede overall throughput.

A still further object of the present invention is to provide a screw extruder that has symmetrically balanced high stress regions which avoid possible deflection of the central screw.

A yet further object of the present invention is to provide a multi-screw extruder that provides improved dispersive mixing over present multi-screw extruders.

An additional object is to provide a screw extruder with modular, exchangeable mixing sections.

A further additional object is to provide a screw extruder with dispersive mixing elements which can be used in injection and blow molding operations and which provides improved dispersive and distributive mixing.

Briefly, one preferred embodiment of the present invention is a screw extruder having a barrel which has a bore defining an inner surface and one or more extruder screws, positioned within the bore. The extruder screw or screws include a central shaft and one or more screw flights. The extruder screw or screws further including one or more dispersive mixing elements which interact with the inner surface of the barrel to form one or more progressively narrowing passages through which material is forced into multiple regions of high elongational and shear stress.

A second preferred embodiment of the present invention is a screw extruder having a barrel, the barrel having a bore defining an inner surface; and one or more extruder screws, positioned within the bore. The extruder screw or screws include a central shaft and a number of dispersive mixing elements which are configured and positioned on the extruder screw or screws to form a number of progressively narrowing passages through which material is forced into multiple regions of high elongational and shear stress.

Also presented is a method of extruding material using a screw extruder having pushing face profiles that form progressively narrowing passages in conjunction with barrel inner surfaces to provide improved dispersive mixing.

The described versions of the present invention have many advantages which address the above-mentioned objects. One such advantage of the present invention is that it provides both good dispersive and good distributive mixing.

Another advantage of the invention is that it provides regions of both high elongational and shear stress.

A further advantage of the present invention is that material is repeatedly passed through regions of high stress for improved breakdown of material agglomerates.

Yet another advantage of the invention is that it may be used in a single-screw extruder, which is less costly for its capacity than a comparable twin screw extruder, yet may provide comparable or better dispersive mixing.

A still further advantage of the present invention is that the high stress regions may be in a forward helical orientation, thus reducing pressure drop in the mixing section, and therefore enhancing overall efficiency and throughput.

A yet further advantage of the present invention is that the high stress regions are symmetrically arranged around the central screw, so that deflection is minimized.

An additional advantage of the present invention is that the improved dispersive mixing process can enhance melting, so that if dispersive mixing elements are located in the melting zone of an extruder, it can speed up the melting process and reduce the length required for melting the plastic.

A yet further advantage of the present invention is that the dispersive mixing elements can be used in a screw extruder used for injection molding, compression molding and blow molding operations to provide improved dispersive and distributive mixing.

These and other objects and advantages of the present invention will become clear to those skilled in the art in view of the description of the best presently known mode of carrying out the invention and the industrial applicability of the preferred embodiment as described herein and as illustrated in the several figures of the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The purposes and advantages of the present invention will be apparent from the following detailed description in conjunction with the appended drawings in which:

FIG. **1** is an overhead view of a simplified screw extruder, in which a portion of the barrel has been cut-away;

FIGS. **2**A–K illustrate a variety of prior art mixing sections for distributive and dispersive mixing;

FIG. **3** shows an isometric view of an extruder screw according to one embodiment of the present invention;

FIG. **4** illustrates a cross-sectional view taken through the screw extruder along line A—A in FIG. **1**;

FIGS. **5**A–F shows a variety of flight face profiles which embody the present invention;

FIG. **6** illustrates a plan view of a prior art mixing section corresponding to a detailed view of the prior art mixing section seen above in FIG. **2**G;

FIG. **7** shows a plan view of an improved mixing section according to an embodiment of the present invention;

FIG. **8** is a side view of a screw extruder with a portion of the barrel removed to expose an extruder screw which has been formed according to the present invention;

FIG. 9 is a cross-sectional view taken through the screw extruder along line B—B in FIG. 8;

FIG. 10 shows a perspective view of prior art kneading paddles;

FIG. 11 illustrates a perspective view of dispersion disks, which are a preferred embodiment of the present invention;

FIG. 12 shows a perspective view of a screw extruder of which a portion of the barrel has been cut away, including dispersion disks of the present invention;

FIG. 13 illustrates a side view of prior art kneading paddles including approach angle α;

FIG. 14 shows a side view of the dispersion disks of the present invention, including approach angle α;

FIGS. 15A & B show front and side plan views of a dispersion disk of the present invention;

FIGS. 16A & B show front and side plan views of a further embodiment of a dispersion disk of the present invention;

FIGS. 17A & B illustrate front and side plan views of a prior art kneading paddle;

FIGS. 18A & B show front and side plan views of a modified kneading paddle according to the present invention;

FIG. 19 shows a side plan view of a stack of dispersion disks and interleaved transitional elements according to the present invention;

FIG. 20 shows a side plan view of an extruder screw having tapered slots formed in the screw flights according to the present invention;

FIG. 21 illustrates a side view of the mixing section of a screw extruder showing both wiping flights and mixing flights according to the present invention;

FIG. 22 shows a close-up detail view of the tapered slot between two flights according to the present invention;

FIG. 23 illustrates a view of an extruder screw, where the cylindrical surface has been "unrolled" into a flat surface, the view showing a fluted dispersive mixing section according to the present invention;

FIGS. 24A–D shows a variety of arrangements of wiping and mixing segments which insure complete wiping as according to the present invention, where the cylindrical surface has again been "unrolled" into a flat surface;

FIG. 25 illustrates a perspective view of an extruder screw where the cylindrical surface has been "unrolled" into a flat surface, the view showing a fluted dispersive mixing section according to the present invention;

FIG. 26 shows a perspective view of another embodiment of a extruder screw where the cylindrical surface has been "unrolled" into a flat surface, the view showing a fluted dispersive mixing section according to the present invention;

FIG. 27 illustrates a perspective view of another embodiment of a extruder screw where the cylindrical surface has been "unrolled" into a flat surface, the view showing a fluted dispersive mixing section according to the present invention;

FIG. 28 shows a perspective view of another embodiment of a extruder screw where the cylindrical surface has been "unrolled" into a flat surface, the view showing a fluted dispersive mixing section according to the present invention;

FIG. 29 illustrates a side view of a mixing section of an extruder screw having semi-circular channels, according to the present invention;

FIG. 30 shows an unrolled view of a mixing section of an extruder screw having semi-circular channels, according to the present invention;

FIG. 31 illustrates a side view of a mixing section of an extruder screw including a number of dispersive mixing elements, according to the present invention;

FIG. 32 shows a side view of a mixing section of an extruder screw including a number of another variation in dispersive mixing elements, according to the present invention;

FIG. 33 illustrates a side cut away view of an extruder screw which is used in an injection molding operation, showing a non-return valve in open valve position, according to the present invention;

FIG. 34 shows a cross-sectional view of the extruder screw taken through line 34—34 in FIG. 33;

FIG. 35 illustrates a side cut away view of an extruder screw which is used in an injection molding operation, showing a non-return valve in closed valve position, according to the present invention;

FIG. 36 shows a detail cut-away view of a slide ring used with an extruder screw in an injection molding operation; and

FIG. 37 illustrates a front view of the slide ring seen in side view in FIG. 36.

BEST MODE FOR CARRYING OUT THE INVENTION

A preferred embodiment of the present invention is a screw extruder having improved dispersive mixing. As illustrated in the various drawings herein, and particularly in the view of FIG. 1, a form of this preferred embodiment of the inventive device is depicted by the general reference character **10**.

FIG. **1** illustrates the major portions of a screw extruder **10**, having a central longitudinal axis **11**, and which also has an input end **12** and an output end **14**. Generally, for convenience of reference, the terms "downstream" shall refer to those ends closest to the output portion of the screw extruder and the term "upstream" shall refer to those ends farthest away from the output. The downstream direction is indicated by a large arrow, which shows the direction of material flow. The screw extruder **10** has a barrel **18**. The input end **12** includes an input hopper **20** for feeding in material, and an extrusion die **22** on the output end **14**. A portion of the barrel **18** has been cut away to show the barrel wall **24**, and an inner bore **26**. Positioned within the bore **26** is an extrusion screw **28** having screw flights **30**. Although this version of the preferred embodiment has a single screw, it is to be understood that the screw extruder could contain two or more screws.

FIG. **2** illustrates a variety of prior art mixing sections of extruder screws, as discussed above in the Background Art section.

FIG. **3** illustrates an isometric cross-sectional view of one version of a mixing section of an extruder screw **28** used in the present invention. The general reference character **31** designates the mixing section of the extruder screw **28**. This mixing section can be an integral portion of the overall screw **28**, or it may be a modular section which is combined with other modular sections upon a central shaft to provide varying characteristics which can be customized for different materials and applications. In FIG. **3**, an optional central bore **32** is shown in phantom line for the case where mixing section **31** is a modular section which can be stacked upon an independent central shaft. This mixing section is defined as having a length (L) **33**. The mixing section **32** includes a central shaft **34** and screw flights **30**, which are used to mix the material as well as convey it forward. A screw diameter (D) **35** is defined as the tip to tip distance between flights **30** when positioned on opposite sides of the central shaft **34**. An arrow is included to indicate the direction of rotation. The flights **30** include the forward pushing face **36**, and the rear face **38**. Reference character **40** will be used to refer to the cross-sectional profile of the flight **30**. As will be seen below, it is the shape of this profile **40** that produces the multiple regions of high elongational and shear stress, which are crucial in producing increased dispersive mixing. In this version of the preferred embodiment, slots **42** have been provided to increase distributive mixing. These slots **42** are optional, and their size and placement are subject to considerable variation, as will be apparent to one skilled in the art. Additionally many other distributive mixing devices may be used, including, but not limited to, pins or protrusions which could be round, square, diamond shape or irregular, secondary flights with interruptions, and changes in channel depth or width (defined below).

FIG. **4** shows a cross-sectional view through the screw extruder **10** along line A—A in FIG. **1**. Barrel **18** includes the barrel wall **24** surrounding a central bore **26** which is defined by the barrel inner surface **44**. In this version of the preferred embodiment, the central bore **26** is cylindrical and accommodates a single extruder screw **28**, but it should be understood that the present invention can be used with two or more extruder screws, in which case, the bore **26** cross-section may resemble multiple overlapping circles or ellipses.

The flights **30** of the screw **28** are shown, and in this version of the preferred embodiment there are four flights which are positioned at 90 degree intervals around the circumference of the central shaft **34**. It is to be understood that other numbers of flights such as two, three, five, six, etc. may be used, and their positions around the circumference of the shaft **34** is likewise variable. It is desirable, however, that the flights **30** be symmetrically arranged around the shaft **34** circumference in order that the forces on the shaft **34** are balanced and deflection is minimized. The front pushing faces **36** and the rear faces **38** of the flights **30** are shown, as well as the flight profile **40**. The front pushing faces **36** and the inner surface of the barrel **44** define a progressively narrowing passage **46** into which the material in the bore **26** moves. The rotational movement of the screw **28** causes the material to enter the large end of the passage **46** and to be squeezed as the passage **46** narrows into high stress regions **48**, which are created between the flight tips **50** and the barrel inner surface **44**. The reducing cross sectional area of the progressively narrowing passage **46** causes an increase in the average flow velocity. Thus the high stress regions **48** develop both elongational and shear stresses which are important in providing increased dispersive mixing. The action of the screw **28** rotation ensures that material agglomerates passes through many of these high stress regions **48**, and thus very high quality dispersive mixing may be obtained.

The distance between the barrel inner bore **44** and the central shaft **34** will define the channel height (H) **52**. The distance between the flight tip **50** and the barrel inner bore **44** is defined as the radial flight clearance (δ) **54**. The ratio of the flight clearance **54** to the channel height **52** is defined as δ/H. The distance between the forward pushing face **36** of one flight **30** and the rear face **38** of the next flight **30** on the extruder screw measured circumferentially will be referred to as the channel width **56**. Additionally, the width of the tip of the flight (w_f) will be designated as **58**, although it is quite possible that this w_f **58** may be zero, depending on the flight face profile **40**. Indeed, the profile shown in FIG. **4** is a smooth curve at the tip **50** and thus the flight tip width **58** is zero in this case.

FIG. **5** shows a variety of pushing face profiles **40** of the screw flights **30** which can be used in conjunction with the barrel wall **24** to produce progressively narrowing passages **46** to force material into high stress regions **48**. It should be understood that many other variations in profile are possible, and the present invention is not limited to the profiles shown.

The versions of the preferred embodiment discussed so far have had a "positive helix angle" or forward flighted configuration. In a forward flighted screw, the pushing flight face moves the material forward toward the output end of the extruder. Returning to FIG. **1**, a positive helix angle (ϕ) **60** can be seen as measured between the face of a screw flight **30** and a vertical reference line **63**. It is also possible to have a rearward flighted configuration. In this case, the pushing flight face moves the material backward toward the feed opening of the extruder. It is also possible to have a neutral flight configuration. In this case, the flight angle is ninety degrees, and the pushing flight face moves the material only in the circumferential direction.

In a screw extruder **10**, it is possible to have a mixing section that contains a negative helix angle. The sections of the screw which are upstream from the mixing section may still have a positive helix angle in order to make sure that the material is conveyed toward the output end **14** effectively. Thus it should be understood that the present invention **10** may be practiced with variations which include negative helix angles. It is anticipated that the extruder screw **28** may be made to be "modular", having a central shaft upon which mixing sections of varying geometry may be stacked to be adaptable to various materials and operations.

One type of modular mixing section which may be employed is the Maddock mixing section, which was discussed in the background art section and shown in FIG. **2G**. FIG. **6** PRIOR ART shows a Maddock mixing section in more detail. The Maddock has longitudinal splines that form a set of semicircular grooves. Alternate grooves are open on the upstream and downstream ends. Material that enters the inlet grooves **70** is forced to pass over the mixing barrier flights **72**, which are shown as cross hatched areas, before reaching the outlet grooves **74**. While passing over the mixing flights **72**, the material is subjected to high shear stress. This can produce some dispersive mixing, but this prior art mixing section only subjects material to a single pass through the high stress region.

In contrast, FIG. **7** shows another preferred embodiment of the present invention in which a multi-flight mixing section **80** can be incorporated in a modular fashion to a screw extruder. Material is introduced through the inlet grooves **70** as before, but must pass over a series of mixing barrier flights **82** before reaching the outlet grooves **74**. In passing over this series of flights **82**, the material must repeatedly pass through high stress regions. Additionally, the barrier flights **82** can include a number of progressively narrowing passages **46** to produce regions of high elongational stress **48**, thus achieving much better dispersive mixing.

It should be understood that the use of multiple mixing barriers can be used in many different configurations to improve dispersive mixing from that achieved by the prior art. A further example would be to improve the blister ring mixer seen in FIG. **2J** of the prior art by using a series of small rings with wedge-shaped leading edges to create multiple high stress regions. Additionally, similar modifications can be made to all fluted mixers such as the Egan, (FIG. 2H), the Zorro, the Troester, etc.

In designing extruder screw mixing sections for good dispersive mixing, there are several variables which can be adjusted to optimize results. According to Tadmor and Manas-Zloczower, (Z. Tadmor and I. Manas-Zloczower, Advances in Polymer Technology, V.3, No.3, 213–221 (1983)), the passage distribution function can be written as:

$$G_k = \frac{\lambda^k e^{-\lambda}}{k!}$$

where k is the number of passes through the clearance, the dimensionless time $\lambda t_r/\bar{t}$ is the ratio of the residence time t_r and the mean residence time of the control volume $\bar{t}$. The residence time for a Newtonian fluid can be approximated as follows:

$$t_r = \frac{2z}{v_{bz}(1-r)}$$

where z is the helical length of the screw section considered, V_{bz} the down-channel barrel velocity, and r the throttle ratio (pressure flow rate divided by drag flow rate). The mean residence time can be determined from:

$$\bar{t} = \frac{2WH}{\delta v_{bx}\left(1 + \frac{W}{w_f}\frac{\delta^2}{H^2}\right)}$$

where W is the channel width, H the channel depth, δ the radial flight clearance, and w_f the flight width. The dimensionless time can be written as:

$$\lambda = \frac{L\delta\left(1 + \frac{W}{w_f}\frac{\delta^2}{H^2}\right)}{WH(1-r)\cos\varphi}$$

where L is the axial length corresponding to down-channel distance z. The fraction of the fluid experiencing zero passes through the clearance is:

$$G_0 = e^{-\lambda}$$

The G_0 fraction should be low to make sure that most of the fluid experiences at least one or more passes through the clearance. In a simple conveying screw the G_0 fraction is usually around 0.9, which means that most of the fluid passes through the extruder without ever passing through the clearance. The expressions above can be used to determine the minimum value that will yield a G_0 less than 0.01, meaning that less than one percent of the fluid will not pass through the clearance at all. This is achieved when the dimensionless time $\lambda > 4.6$. For certain values of L, H. W, r, φ, w_f we can then determine how large the flight clearance δ has to be to make $\lambda > 4.6$ or $G_0 < 0.01$.

When L=3W, r=0, and φ=17.67°, the ratio of δ/H has to be about 0.8 to achieve a $G_0 < 0.01$. Clearly, with such a high ratio of δ/H it will be almost impossible to create large stresses in the clearance and to accomplish effective dispersive mixing. From equation 4 it is clear what geometrical variables we have to change to achieve a low G_0 fraction at a small clearance. We can do this by 1) increasing L, the length of the mixing section, 2) increasing φ, the helix angle, 3) reducing w_f, the width of the flight, and 4) increasing the number of flights.

If the helix angle is increased from 17.67 to 60 degrees with the other values being the same, the δ/H ratio has to be about 0.35 or greater for the G_0 fraction to be less than 0.01. This value is still rather larger, but substantially better than 0.8. The δ/H ratio can be further reduced by increasing the length of the mixing section or reducing the flight width or by increasing the helix angle even more. This procedure allows a first order determination of the design variables. Further refinement of the initial values can be obtained from computer simulation.

It is estimated that in prior art screw extruders with a simple conveying screw, G_0, the fraction of material that does not pass through the clearance, is typically 0.9. This means that a great deal of material never passes through high stress regions, and thus dispersive mixing is poor.

In the present invention, it is desired that G_0 is less than 0.01, and therefore greater than 99% of the material will pass through a region of high stress. It is anticipated from the above formulas that for this value of G_0, in order to achieve a δ/H ratio in a reasonable range of 0.05 to 0.3, the helix angle (φ) will lie in the range of −90° to −30° and +30° to +90°, the length of the mixing section (L) will lie in the range of 1 to 20 times the bore diameter, and the width of the screw flight at the tip (w_f) will lie in the range of 0 to 0.5 times the diameter, D.

It should be understood that although the preferred range of helix angles is −90° to −30° and +30° to +90°, values in the range from +30° to −30° will work as well.

Multiple passes through a high stress region are necessary to break down agglomerates. Thus even in mixing sections with very low values for G_0, there is no assurance that good dispersive mixing will be achieved. For example, in the Maddock prior art mixer, all the material has to pass through the high stress region, but it only passes through this region once, which is insufficient.

Another parameter of interest is the ratio of flight clearance to the screw diameter or δ/D. This gives an indicator of how much material flows through the high stress regions, and thus is proportional to how well the material is dispersively mixed. The higher this number is, the better the dispersion can be expected. For prior art single screw extruders, this δ/D figure is typically 0.001, and for prior art twin screw extruders, this δ/D figure improves to 0.005. In contrast, the δ/D value for the various preferred embodiments of the present invention is 0.005 to 0.250. When the δ/D number becomes too high the stresses that will be generated may be too low to accomplish dispersive mixing. The clearance should be small enough to be able to generate high enough stresses but large enough to allow sufficient material to flow through it.

The flights of a screw extruder can convey material in the downstream direction and can also serve to prevent material from building up on the walls of the extruder barrel. This latter function is known as "wiping" and it is possible to have elements that perform this wiping separately from the function of conveying material, although typically the functions are combined. It is also possible that wiping and conveying can be performed by one set of screw flights, while mixing is done by a second set of flights. This second set of flights may be in a separate modular section, or in the same section by incorporating this second set of flights between the conveying/wiping flights. The mixing flights do not have to have the same helix angle as the conveying/wiping flights, and indeed it may be beneficial that they be different. The helix angle of the conveying flights can be chosen to give the best pumping action, while the helix angle for the mixing flights can be chosen to give the best dispersive mixing action. A functional separation of the two types of flights can thus be achieved, allowing optimization of the overall performance.

FIG. **8** show a screw extruder **90** with a modified central screw **92** in which the mixing flights **94** are included between the conveying/wiping flights **96**.

FIG. **9** is a cross-sectional view of FIG. **8** taken through line B—B. The profile **40** of the mixing flights **94** can be seen to produce a progressively narrowing passage **46** in the barrel **18** which again forces material into regions of high stress **48**. This configuration causes enhanced material dispersion while the wiping/conveying flight **96** has been designed for optimal pumping characteristics.

As mentioned above, it is also possible to have a variation in which the helix angle is ninety degrees. This is accomplished by using straight disks which are offset from each other at varying rotational angles. For a single screw extruder, this version of the preferred embodiment is similar to kneading paddles used in twin screw extruders, but with the important difference and advantage that the geometry of the disks can be optimized for production of effective elongational and shear stress, rather than being constrained by the need to trace the outline of a second screw.

FIG. **10** Prior Art shows the configuration of the kneading paddles in one screw of a twin screw extruder as in the prior art. In contrast, FIG. **11** illustrates a second preferred embodiment **100** of the present invention for use in a single screw extruder having dispersion disks **102** aligned upon a central longitudinal axis **104**. The pushing flight faces **106** have a pronounced wedge shape, and the trailing flight face **108** is flat. Stagger angle β **109** is shows the rotational offset of the successive disks. In a similar manner to that discussed above in regard to the profile of the pushing flight faces **30** in the positive helix angle embodiment, the profiles of the pushing faces **106** of the dispersion disks **102** are capable of much variation, such as elliptical sections, triangles, circular sections, etc. Additionally, these dispersion disks **102** may also be modular, and may be stacked upon a central shaft to provide various mixing characteristics.

FIG. **12** shows such a version of the preferred embodiment **100** in which dispersion disks **102** having a ninety degree helix angle have been fixedly stacked upon a central shaft **110**. A portion of the barrel **118** has been cut away to show the orientation of the disks **102**. A central longitudinal axis **104** has again been included for easy reference. Elongational and shear stress necessary for good dispersive mixing are produced in the high stress regions **120** between the paddle tips **122** and the barrel inner surface **124**. The main dispersive mixing action will occur in the narrowing region formed by the pushing flight face **106** and the inner barrel surface **124**. Material is forced into the progressively narrowing passage **126** by drag flow caused by the relative motion between the screw and the barrel surface **124**.

FIG. **13** PRIOR ART and FIG. **14** show a comparison of the profiles of the prior art and the dispersion disks of the present invention. In FIG. **13**, a prior art kneading paddle in a barrel of a screw extruder is illustrated with line **128** drawn tangent to the surface of the paddle at the tip. A second line **130** is drawn tangent to the point on the barrel's inner surface which intersects the projection of line **128**. The two lines **128** and **130** define an angle α which is designated as **132**. The geometry of the kneading paddle is constrained by the necessity of mating with a second paddle whereby the tip of the first paddle wipes the second and thereby traces the required contour. Angle α **132**, which defines the entrance angle to the passage past the tip, is severely limited by this design constraint, and is not optimized for dispersion of material.

In contrast, the profile of a preferred embodiment of present invention **100** is shown in FIG. **14**. A dispersion disk **102** is illustrated in the bore **124** of a screw extruder **10**. A line **134** is shown tangent to the disk's surface near the tip **122**. As before, a second line **136**, tangent to the projected point on the barrel's inner surface **124**, defines an angle α **138**. Since the geometry of the dispersion disk **102** is not dictated by the necessity to trace the outline of an adjacent paddle, the angle α **138** can be much more acute and can be designed to produce excellent dispersion of the material. It is anticipated that this angle α **138** will lie in the range of zero to **350**, while the typical angle α **132** found in prior art kneading paddles from twin screw extruders is 35° to 50°. By way of comparison, this corresponding approach angle α in prior art single screw extruders is typically 90°, since there is no progressively narrowing passage provided.

While the material is forced all the way into a progressively narrowing passage, and through it, dispersive mixing action will be efficient. However, the polymer melt will have a tendency to bypass the high stress regions and take the path of least resistance by flowing around them as can be seen in FIGS. **15**A & B. In FIG. **15**A, a dispersion disk **102** is seen in profile as well as a small portion of the barrel's inner surface **124**. The high stress region **120** is shown between the disk tip **122** and the barrel's inner surface **124**. FIG. **15**B shows a front plan view of the same dispersion disk **102** with flow of material **140**. Material **142** is shown flowing around the sides of the disk tip **122**. This will reduce the efficiency of the dispersive mixing action.

This problem can be greatly reduced by the addition of a barrier wall in the high stress region to close off the bypass route. FIGS. **16**A & B show another preferred embodiment **150** of the present invention in which two barrier walls **154** have been added. FIG. **16**A shows a side plan view of the modified dispersion disk **152** with barriers **154** at the tips **122**. FIG. **16**B shows a front plan view of the modified dispersion disk **152** with material flow **140** which is channeled through the high stress region **120**. The efficiency of the dispersive mixing is thus enhanced.

This modification can also be used with prior art kneading paddles to improve performance as seen in FIGS. **17**A & B and **18**A & B. FIGS. **17**A & B show side and front plan views of a prior art kneading paddle without modifications. FIG. **18**A shows a side plan view of a modified kneading paddle **160** which has been improved by means of the present invention. A groove **162**, seen in dashed line in FIG. **18**A, has been cut into the surface of the paddle **160**. FIG. **18**B shows a front plan view of the modified paddle **160** with the groove **162** included. This groove **162** can channel material into the region between the tip **164** and the barrel wall **124**. Although the paddle's shape is still largely dictated by the tracing of its companion paddle, the region in the groove **162** can be angled differently to improve material dispersion. This is expected to produce improved performance, although it may not reach the efficiency of the dispersion disks **102**.

There is a common problem which exists in regard to mixing elements which have a neutral helix angle, such as both kneading paddles and dispersion disks. This problem is that there may be stagnation points which exist at the transition between the different disks. This condition can be corrected by the use of transition elements between the straight disks. FIG. **19** illustrates one form that transitional elements might take. Dispersion disks **102** are interleaved with one or more transition elements **166**. In this version of the preferred embodiment, the transition elements are flighted elements with a helix angle between zero and 90°. These elements **166** may be basically shaped as twisted dispersion disks with the angle of twist equal to the stagger angle **109** (see FIG. **11**) of the dispersion disks **102**. Transition elements flights **168** are shown connecting the tips **122** of the disks **102**. These elements provide a gradual transition from one dispersion disk to another and aid the flow of material while still maintaining the dispersive mixing capability. It is to be understood that these transition disks may also be used with kneading paddles of the prior art to improve material flow.

It should be further understood that the improvements of the present invention can be used in screw extruders that contain multiple screws. Twin-screw extruders can be co-rotating with screws rotating in the same direction, or counter-rotating with screws rotating in the opposite direction. There are also triple-screw extruders, quadruple-screw extruders, and screw extruders with ten screws arranged in a circular pattern. All varieties of screw extruders can benefit from improved dispersive mixing by using the preferred embodiments of the present invention which are presented above. Increasing the number of high stress regions by using flights with the profiles shown above, is a technique that can be useful in any of multiple as well as single screw extruders. Therefore, in addition to the above mentioned examples, various other modifications and alterations of the inventive device/process **10** may be made without departing from the invention.

Another variation of extruder screw geometry having different dispersive mixing elements is shown in FIG. **20**. This extrusion screw **200** has a number of screw flights **202**, each flight having a mixing portion **204** and a wiping portion **206**. The flights **202** are interrupted by slots **208** which improve not only distributive mixing, but which are tapered to improve dispersive mixing as well. The slots **208** have a taper angle **210**, which is preferably in the range of 20 to 60 degrees. The tapering of the slots **208** provide narrowing channels **212**, which once again create multiple regions of high elongational stress **214**.

Two other angles of interest are the slot pushing flank angle **216** and the slot trailing flank angle **218**, which are shown in FIGS. **20**, **21** and **22**. These angles are measured in a clockwise rotation from a vertical reference. In FIG. **20**, the trailing flank angle **218** is equal to zero degrees, while in FIGS. **21** and **22**, this is a non-zero angle. FIG. **22** shows a detail view of two adjacent wiping flight portions **206**, wherein the importance of this non-zero slot trailing flank angle **218** can be seen more easily. The solid outline of the non-shaded area defines a slot trailing flank **220** which has a zero angle. As the screw rotates, there remains a region **222**, which is not wiped by the flight **206**, assuming that there is not another wiping flank whose travel overlaps this region. However, if the shaded area in the dashed outline **224** is added to the wiping flight **206**, the slot trailing flank angle **218** is large enough (in this case, about 35 degrees) that the region **222** is wiped in the course of the screw rotation. Although this slot trailing flank angle **218** has been increased, the slot **208** still tapers as shown by taper angle **210**, thus producing effective dispersive mixing. This configuration of wiping flights which have a tapering slot but no regions which are left unwiped in the course of screw rotation will be referred to as "fully wiping flights" **226**.

The trailing slot flank angle that is required to achieve full wiping depends on the width of the slot, the thickness of the flights and the helix angle of the screw flights. It is also possible that the wiping flight segments may overlap in their path of travel, thus making the angle of the slot trailing face less important.

Another feature which is apparent from FIG. **21** is that a flight segment **228**, which is defined as a portion of the screw flight **202** bounded at the ends by slots **208**, can be entirely of a mixing portion **204** or entirely of a wiping portion **206**. FIG. **21** shows segments which are entirely of a mixing character to make mixing segments **234**, and segments which are entirely of a wiping nature to form wiping segments **236**. Indeed, for ease of manufacture, this separation of portions into discrete segments is very desirable. It is to be understood that any combination of mixing portions and wiping portions is possible, whether combined onto one segment or separated into different segments. All of these combinations are to be considered included in the scope of this invention.

For an example, a mixing section can be designed that has wiping segments **236**, without any mixing segments, but with tapered slots **208** between the segments **236**. The flight **202** composed of these wiping segments **236** may be a fully wiping flight **226**, but is not necessarily so. Dispersive mixing in this case would then be achieved solely by the elongational flow generated in the tapered slots **208**. Even without any segments having mixing portions, significant improvement in mixing performance is created. Especially when modular mixing segments are stacked upon a central shaft, as discussed above, the relative lengths and numbers of the mixing segments **234** and the wiping segments **236** can be easily changed, depending on whether more wiping or mixing is desired.

FIG. **23** shows a four lighted mixing screw with angles and dimensions which have been found to be especially efficient in operation. This figure presents an "unrolled view", which simulates the pattern made by the screw flights if they were rolled onto a flat surface. Thus dimension 238 corresponds to the circumference or a measurement of πD where D is the diameter of the screw. Wiping flight segments **236** are shown in black, and mixing flight segments **234** are shown in white. It is to be understood that many other combinations of angles and dimensions are contemplated by the present invention, as long as the tapered slots are used to provide improved dispersive mixing. Also, the number of flights is not limited to four.

The helix angle ϕ **60** is shown as measured from a vertical reference line **63**. A preferred range of angles for the helix angle ϕ **60** is between 20–90 degrees, the slot pushing flank angle **216** preferably is in the range of 0–90 degrees, the slot trailing flank angle **218** preferably is in the range of 0–50 degrees, the slot width preferably is in the range of 0.02–0.25D, and the flight width preferably is in the range of 0–0.5D.

One preferred example of a configuration of these variables which lie in these ranges is seen in FIG. **23**. Here, the helix angle ϕ **60** is 45°, the slot pushing flank angle **216** is also 45°, and slot trailing flank angle **218** is 20°. The slot width **240** is approximately 0.05D and the flight widths are approximately 0.1 OD. This configuration allows for slot taper angles **210** of approximately 25°, and due to the non-zero slot trailing flank angle **218**, all four flights are fully wiping flights.

It is desirable that the entire circumference of the barrel be fully wiped in order to prevent material build-up and impediments to flow. FIGS. **24**A–D illustrate various arrangements of wiping segments **236** and mixing segments **234** which insure complete wiping. Once again, the figures are shown in unrolled view. For ease of drawing in the scale presented, the taper angles of the slots are not shown in these figures, but it is to be understood that the slots are indeed tapered, and the flights are fully wiping flights. The dark segments depict the wiping segments **236**, while the mixing segments **234** are white. FIG. **24**A shows a configuration where every flight **202** is composed of one wiping segment **236** to three mixing segments **234**. This is referred to as "every flight is ¼ wiped". By the same nomenclature, FIG. **24**B shows every other flight is ½ wiped, FIG. **24**C shows one flight completely wiped, and FIG. **24**D shows two flights ⅙ wiped and two flights ⅓ wiped.

A new type of fluted mixing section **300** including another type of dispersive mixing element is illustrated, again in "unrolled view", in FIG. **25**. In this variation, the shaft portion **304** of the screw **302** is provided with ramp sections **306** which act in conjunction with mixing flight sections **308** to provide multiple regions of elongational stress **310**. The ramp sections **306** provide a series of crests **312** and troughs **314**. The approach to the crests **312** provide regions of increased pressure and elongational stress which are bounded on the upstream side by a main flight section **316** which, along with the mixing flight sections **308**, serve to define a channel **318**. The main flight sections **316** are designed to maintain the material in the channel **318**, and convey the material downstream. The downstream side is bounded by a mixing flight **308** which has a narrowing profile **320**, and may containing mixing grooves **322** or other distributive mixing elements. As the material is forced up the ramp **306**, it therefore either passes through the high stress region **310** at the crest **312**, or flows over the mixing flight section **308** into a region of relatively lower pressure at an adjacent trough **314**. In either case, dispersive mixing is enhanced by the passage of material through multiple regions of elongational stress **310**.

Generally, within the fluted mixing section **300**, a number of dispersive regions **330** are formed. Each dispersive region **330** has at least one inlet portion **332**, and at least one outlet portion **334**. The dispersive regions **330** are configured so that material must pass through a high stress region **310** as it leaves the outlet portion **334** of the dispersive region **330**, and each outlet portion **334** connects to the inlet portion **332** of an adjacent dispersive region **330**. This guarantees that material must pass through multiple regions of high stress thus causing more effective dispersive mixing.

In this embodiment, the inlet portion **332** of the dispersive region **330** corresponds to the troughs **314**, and the outlet portions **334** are formed by the crests **312**, as well as the mixing flights **308** over which the material must pass before reaching the next trough **314**. It should be noted that both types of outlet portions **334**, the crests **312** and mixing flights **308** have the same type of narrowing profile which produces the regions of high elongational stress which provide improved dispersive mixing.

The screw **302** illustrated is configured with the crest of an upward ramp abutting the crest of the next downward ramp and the trough of that ramp abutting the trough of the next upward ramp. However, it is to be understood that a screw could be configured so that the crest of one ramp abuts the trough of the next ramp, or in other words, there could be a series of upward ramps, or alternately, downward ramps. Of course, it will be apparent to those skilled in the art that any combination of upward and downward ramps may be used, and the combinations produced may be tailored to requirements of the extrusion materials.

A further variation in the fluted mixing section **400** with dispersive mixing regions is shown in FIG. **26**, also in "unrolled view". The shaft **404** in this variation is configured with a number of main flights **416**, which serve to confine the flow of material to channels **418** therebetween. Within these channels **418** are a number of wedge-shaped barrier flights **408** which serve to create regions of elongational stress **410** as the material is forced up the triangular ramp **406** of the flights **408**. The flights **408** have a drop face **424** over which the material must flow to escape the high pressure region, and this drop face **424** may be configured with distributive regions **422** such as teeth or mixing grooves to further mix the material.

Again, the channels **418** can be considered to be made up of a number of dispersive regions **430**, each having at least one inlet portion **432**, and at least one outlet portion **434**. Material must pass through a high stress region **410** as it leaves an outlet portion **434** of the dispersive region **430**, and each outlet portion **434** connects to the inlet portion **432** of an adjacent dispersive region **430**. As before, this guarantees that material must pass through multiple regions of high stress thus causing more effective dispersive mixing.

The fluted mixer **400** shown in FIG. **26** has three such barrier regions **408** thus providing three passes through a high stress region **410**, but of course the number of barrier regions included is subject to much variation and not limited to three.

FIG. **27**, another "unrolled view", shows a yet further variation, designated as fluted mixing section **500**, which again uses a number of main flights **516** on the shaft **504** to create channels **518** in which material flows. A number of wedge-shaped barrier flights **508** again act to create regions of high stress **510** before the material flows down the drop faces **524**, which again may be configured with distributive elements **522**. Again, dispersive regions **530** may be identified having at least one inlet portion **532** and at least one outlet portion **534**.

FIG. **28** shows a variation of the embodiment of FIG. **27**, in which additional triangular ramp elements **520** have been added to the barrier flights **508** to avoid the creation of stagnation points, where material may otherwise accumulate. The channel **518** is shown from the upstream end in order to illustrate the features more clearly.

As before, the channels **518** seen in FIGS. **27** and **28** can be considered to be composed of a number of regions **530**, each of which has at least one inlet portion **532**, and at least one outlet portion **534**. The dispersive regions **530** are configured so that material must pass through a high stress region **510** as it leaves the outlet portion **534** of the dispersive region **530**, and each outlet portion **534** connects to the inlet portion **532** of an adjacent dispersive region **530**. This guarantees that material must pass through multiple regions of high stress thus causing more effective dispersive mixing.

Much the same principle works in the embodiment shown in FIGS. **29** and **30**. FIG. **29** shows a side view of an extruder screw mixing section **550**, while FIG. **30** illustrates an unrolled view of the same mixing section **550**. Referring now to both figures, the shaft **552** has a diameter just slightly smaller than the diameter of the barrel (not shown). Into this shaft are machined a number of semi-circular channels **554**, preferably created by ball milling. Since the umilled portion of the shaft **552** fills the barrel except for enough clearance to allow for rotation, these unmilled portions act as barrier flights **556** to direct the flow of material. A number of these flights, shown in cross-hatch, are then machined to create mixing flights **558** each of which have a narrowing profile between a channels' **554** outlet portion **560** and the inlet portion **562** of a neighboring channel **554**. This provides multiple regions **564** of high elongational and shear stress, as before. Arrows show representative flow paths of material, by which it can be seen that material must pass through many of these regions **564** of high stress before leaving the mixing section, thus insuring excellent dispersive mixing. The mixing flights **558** can of course include other mixing elements such as pins, grooves, etc.

An advantage of this embodiment is the ease with which it can be manufactured, since ball milling is a well-known and relatively inexpensive method of manufacture.

FIG. **31** illustrates a side view of an extruder screw **600**, which has another variety of dispersive elements. A central shaft **602** has a number of dispersive elements **604**, which, in this embodiment, are roughly diamond shaped pins or protrusions. The shape and position of these elements **604** on the shaft **602** again create gradually narrowing passages **606**, which create multiple regions **608** of high elongational and shear stress.

FIG. **32** illustrates another variation of this concept. A side view of a extruder screw **600** is shown in which dispersive elements **610** are pins or protrusions which have a triangular profile. Again, narrowing passages **606** create multiple high stress regions **608**. This arrangement has the advantage that the dispersive elements are arranged in a helical configuration, which can reduce the pressure drop across this region.

It is to be understood that many variations of this arrangement could be used, which would be obvious to one skilled in the art. Many other types of polygons or non-polygons could be used as the dispersive elements. If triangular elements are to be used, they could be of many different types such as isosceles triangles, right triangles, etc. and the triangles could assume many different positions and orientations on the shaft, as long as they form the required narrowing passages for high elongational and shear stress. All such variations are within the scope of the present invention.

The dispersive elements described and pictured may also be used in injection molding machines. The mechanisms used in these machines are also sometimes called "plasticating units". However, these plasticating units may be so similar in structure to the mechanisms in regular screw extruders that for the purposes of this application, the term "screw extruder" shall be understood to include both injection molding machines and other types of molding machines such as blow molding machines, compression molding machines, etc. Effective dispersive mixing is important to all these types of machines. Thus the creation of multiple progressively narrowing passages which form regions of high elongational and shear stress such as are provided by the present invention is an very valuable improvement to any machine of this type.

FIG. **33** shows a screw extruder **700** which is being used in an injection molding operation. The injection molding machine is shown in an "open valve" position, which will be described below. The arrows included show the direction of material flow and point in a downstream direction. As before, the screw extruder **700** includes an extruder screw **701** which includes a number of screw flights **702**. The screw **701** includes a central shaft **706** upon which two slotted rings are mounted. A slide ring **708** (shown in cut-away view) is free to move in an axial direction along the shaft's longitudinal axis **712**. A stationary ring **710** is fixed to the shaft **706** and rotates as the shaft rotates and is thus "stationary" with reference to this shaft. The stationary ring **710** includes a number of dispersive mixing elements **714**. As in the other embodiments previously described, the dispersive elements **714** are shaped and positioned upon the screw **701** to produce gradually narrowing passages **716** which, again, produce multiple regions of elongational and shear stress **718**. It will be obvious to one skilled in the art that there may be two or more stationary rings on the shaft, and that these rings may be in the form of modular sections which can be stacked upon the central shaft.

Although not visible in this view, the inner circumference of the slide ring **708** is also formed with dispersive elements, which will be discussed below. The chamber where the injection material is mixed and plasticized is referred to as the plasticizing chamber **720**. In FIG. **33**, it includes the area within the barrel **704** in the downstream direction from the shaft shoulder **722**.

The injection molding operation demands that appropriate pressure be generated within the barrel **704** and that injection material be well plasticized before being injected into the mold. To accomplish these purposes, nearly all injection molding machines include a non-return valve, which, when open, allows material to enter the plasticizing chamber, but when closed prevents material from exiting the plasticizing chamber, and allows pressure to build in the chamber. In the present invention, the non-return valve is an assembly formed from the shaft shoulder **722** and the upstream shoulder **724** of the slide ring **708**. The non-return valve assembly shall be indicated by the number **726**.

When the non-return valve **726** is in open position, the mold (not shown) is closed. The screw **701** rotates and moves backwards in the barrel **704**. Material then flows into the plasticizing chamber **720** as indicated by the arrows. The material passes through the dispersive elements on the inner circumference of the slide ring (see also FIG. **34**) and then through the dispersive elements **714** on the stationary ring **710**, and are mixed as the screw **701** turns.

FIG. **34** shows a cross-sectional view of the screw extruder **700** as taken through line **34**–**34** in FIG. **33**, including the barrel **704**, and the stationary ring **710** with the dispersive mixing elements **714**.

FIG. **35** illustrates a side cut-away view of a screw extruder **700** used in an injection molding operation in which the non-return valve is now in the "closed valve" position. The screw **701** has now moved forward in the barrel **704** so that the shaft shoulder **722** contacts the upstream shoulder **724** of the slide ring **708**, thus closing the non-return valve **726**. The plastic melt can now be pushed into the mold without material leaking backwards.

FIG. **36** shows a detail cross-sectional view of the slide ring **708** showing the dispersive mixing elements **714** on the inner circumference of the ring **708**. The narrowing passage **716** and the high stress regions **718** are also shown.

FIG. **37** illustrates a front view of the slide ring **708** seen in side view in FIG. **36**. The dispersive elements **714** and the high stress regions **718** are shown.

Therefore, in addition to the above mentioned examples, various other modifications and alterations of the inventive device/process **10** may be made without departing from the invention. Accordingly, the above disclosure is not to be considered as limiting and the appended claims are to be interpreted as encompassing the true spirit and the entire scope of the invention.

INDUSTRIAL APPLICABILITY

The present screw extruder **10** is well suited generally for application in any mixing process where a solid or liquid ingredient needs to be mixed dispersively in a viscous fluid. This may be the dispersion of solid agglomerates in a viscous fluid or the dispersion of liquid droplets in a viscous fluid. It is particularly well suited for use in mixing blends of polymers or for mixing additives to polymers prior to extrusion forming.

Applications in the polymer field include the dispersion of solid pigments into polymers for making colored plastic products. Particularly where uniformity of color is important, it is very advantageous that the color particles be well mixed dispersively and broken down into smaller agglomerates than may be possible through merely distributive mixing.

The present invention **10** can also be used to improve the dispersion of incompatible polymer components into a polymer matrix to produce polymer blends and alloys. Good dispersive mixing can be important in obtaining uniform material properties such as tensile strength, durability, etc. Reinforcing fillers can be added to a polymer matrix to produce increased stiffness with greater uniformity using the present invention **10**.

When manufacturing conductive or semi-conductive materials, the dispersion of conductive fillers in a polymer matrix is enhanced by use of the present invention **10**. The dispersion of magnetic fillers in plastic magnets, and dispersion of solid fillers for increased resistance to oxidation can both be improved when using the improved dispersive mixer **10**. The present invention **10** is also useful in the manufacture of rubber adhesives.

The viscous fluid to be dispersively mixed does not have to be plastic or polymer based. It is possible to mix food products such as dough, mashed potatoes, cooking oil, a slurry of grapes or fruit concentrates, honey or peanut butter. It can also be petroleum products like oil or rocket fuel, etc. All of these materials may benefit from the improved dispersive mixing which is provided by the present invention **10**.

Additionally, since the mixing elements of the present invention can be made to be modular, it is possible to customize configurations for optimum performance with a particular material. The improvements of the present invention **10** may thus also be incorporated into existing screw extruders at reduced cost. Particularly, improvements to prior art kneading paddles may be made by using conventional machining methods to include the improved dispersive groove **162** in existing machines for little cost. For even better performance, dispersion disks **102**, which may be manufactured to the same diameter and standard shaft fitting dimensions as the prior art paddles, may replace the kneading paddles.

Another consideration which makes improved dispersive mixing desirable, is that as the size of unmelted particles is reduced by better dispersive mixing, these particles are more easily melted. Thus if more efficient dispersive mixing can be generated in the melting zone of the extruder **10**, it can speed up the melting process and the required length of the melting zone can be decreased. This would allow more compact and efficient extruders to be designed. Factory floor space could be reduced at great savings. Also, as the melting process is increased, overall throughput of the extruder **10** is increased, resulting in an increase in overall efficiency, with attendant cost savings.

The screw extruder **700** having dispersive mixing elements **714** which are positioned to form progressively narrowing passages **716** is also useful in injection molding, blow molding, compression molding and other kinds of molding operations.

For the above, and other, reasons, it is expected that the screw extruder **10** of the present invention will have widespread industrial applicability. Therefore, it is expected that the commercial utility of the present invention will be extensive and long lasting.

What is claimed is:

1. A screw extruder comprising:

a barrel, said barrel having a bore defining an inner surface; and

at least one extruder screw, positioned within said bore, said at least one extruder screw including a central shaft and at least one screw flight, said at least one extruder screw further including at least one dispersive mixing element which interacts with said inner surface of said barrel to form at least one progressively narrowing passage through which material is forced into at least one region of high elongational and shear stress.

2. The screw extruder of claim **1** wherein:

said at least one dispersive mixing element includes at least one tapered slot formed in said at least one screw flight, said at least one tapered slot forming at least one progressively narrowing passage through which material is forced into at least one region of high elongational and shear stress.

3. The screw extruder of claim **2** wherein:

said at least one tapered slot has a taper angle which is in the range of 20 to 60 degrees.

4. The screw extruder of claim **1** wherein:

said at least one flight includes a mixing portion and a wiping portion.

5. The screw extruder of claim **1** wherein:

said at least one flight includes discrete mixing segments and wiping segments.

6. The screw extruder of claim **1** wherein:

said at least one flight has only wiping segments.

7. The screw extruder of claim **2** wherein:

said at least one flight includes at least one non-zero slot pushing flank angle.

8. The screw extruder of claim **2** wherein:

said at least one flight includes at least one non-zero slot trailing flank angle.

9. The screw extruder of claim **1** wherein:

said at least one flight is a fully wiping flight.

10. The screw extruder of claim **2** wherein:

said extruder screw has a Diameter dimension;

said flight has a helix angle, a slot trailing flank angle, a slot pushing flank angle, a slot width and a flight width;

said helix angle is in the range of 20–90 degrees;

said slot pushing flank angle is in the range of 0–90 degrees;

said slot trailing flank angle is the range of 0–50 degrees;

said slot width is in the range 0.02–0.25 Diameters; and

said flight width is in the range of 0.0–0.5 Diameters.

11. The screw extruder of claim **5** wherein:

said screw extruder has four flights which are arranged in a flight segment configuration, which is a variable to be selected from a group consisting of every flight ¼ wiped, every other flight ½ wiped, one flight is completely wiped, and two flights ⅙ wiped and two flights ⅓ wiped and every flight ⅓ wiped except for the fourth flight.

12. The screw extruder of claim **1** wherein:

said at least one dispersive mixing element include at least one fluted mixing section;

each said fluted mixing section having a plurality of adjacent dispersive regions;

each of said adjacent dispersive regions including at least one inlet portion and at least one outlet portion, and at least one region of high elongational and shear stress; and said adjacent dispersive regions being configured so that an outlet portion of one adjacent dispersive region directs material into an inlet portion of another adjacent dispersive region so that material is forced through multiple regions of high elongational and shear stress.

13. A screw extruder as in claim **12** wherein:

said adjacent dispersive regions of said fluted mixing section include a plurality of barrier flights which create multiple regions of high elongational and shear stress.

14. A screw extruder as in claim **13** wherein:

said barrier flights include ramps which are formed on said central shaft of said extruder screw.

15. A screw extruder as in claim **14** wherein:

each of said ramps has a crest and a trough, said ramps being arranged crest to crest and trough to trough.

16. A screw extruder as in claim **14** wherein:

each of said ramps has a crest and a trough, said ramps being arranged crest to trough.

17. The screw extruder of claim **13** wherein:

said barrier flights are bounded by main flight sections and mixing flight sections.

18. The screw extruder of claim **17** wherein:

said mixing flight sections are formed with wedge-shaped profiles to further create regions of high elongational and shear stress.

19. The screw extruder of claim **17** wherein:

said mixing flights include distributive mixing elements.

20. The screw extruder of claim **13** wherein:

said barrier flights of said fluted mixing section include a plurality of triangular wedge shapes which are formed on said central shaft.

21. The screw extruder of claim **13** wherein:

said barrier flights include distributive mixing elements.

22. The screw extruder of claim **12** wherein:

said fluted mixing section includes a plurality of semi-circular channels.

23. The screw extruder of claim **1** wherein:

said at least one extruder screw is a pair of twin extruder screws.

24. The screw extruder of claim **23** wherein:

said twin extruder screws rotate in counter directions.

25. The screw extruder of claim **23** wherein:

said twin extruder screws rotate in the same direction.

26. The screw extruder of claim **1** wherein:

said at least one extruder screw includes modular sections which are arranged on a central shaft to provide variable mixing characteristics.

27. The screw extruder of claim **1** wherein:

said at least one screw right is a plurality of screw fights which are symmetrically arranged about a central shaft to balance deflection forces.

28. The screw extruder of claim **27** wherein:

the number of screw flights is a variable selected from the group consisting of two, three, four, five, and six.

29. A screw extruder comprising:

a barrel, said barrel having a bore defining an inner surface; and

at least one extruder screw, positioned within said bore, said at least one extruder screw including a central shaft and a plurality of dispersive elements, said dispersive elements being configured and positioned on said at least one extruder screw to form a plurality of progressively narrowing passages through which material is forced into a plurality of regions of high elongational and shear stress.

30. The screw extruder of claim **29** wherein:

said dispersive elements are positioned in a helical configuration.

31. The screw extruder of claim **29** wherein:

said screw extruder includes a slip ring and at least one stationary ring.

32. The screw extruder of claim **29** wherein:

said screw extruder includes a non-return valve.

33. The screw extruder of claim **31** wherein:

said slip ring includes a plurality of dispersive elements.

34. The screw extruder of claim **31** wherein:

said stationary ring includes a plurality of dispersive elements.

35. A method of extruding material from a screw extruder comprising the steps of:

providing a screw extruder including a barrel having input and output ends, a bore defining an inner surface, and an extrusion die at said output end;

providing at least one extruder screw positioned within said bore, each screw including a central shaft, said at least one extruder screw further including a plurality of dispersive mixing elements which interact with said inner surface of said barrel to form progressively narrowing passages through which material is forced into multiple regions of high elongational and shear stress;

introducing extrusion material into said input end of said barrel;

rotating said at least one screw to force said material through said dispersive mixing elements where said material passes through multiple regions of high elongational and shear stress; and

conveying said material towards said extrusion die at said output end to be shaped.

36. The method for extruding material from a screw extruder of claim **35** wherein:

said dispersive mixing elements are selected from a group consisting of tapered slots formed in said flights, fluted sections with ramped barrier flights formed on the central shaft, fluted sections with barrier flights formed on said central shaft which are triangular wedge shapes, barrier flights with triangular profile, diamond shaped protrusions, triangular pins, and protrusions which are positioned on a stationary ring and protrusions which are positioned on the interior of a slide ring.

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